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STUDIES IN ECONOMICS

SMALL COUNTRIES AND INTERNATIONAL TRADE
JOHN H. AUTEN

COSTS OF OPERATING CRUDE OIL PIPE LINES
LESLIE COOKENBOO, JR.

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SMALL COUNTRIES AND INTERNATIONAL TRADE

THE position of small countries in the international economy is an interesting one. Countries like Denmark, New Zealand, and Switzerland achieve high levels of real income based in large measure upon the opportunity for international trade and specialization. On the other hand, these small countries do find their economic fortunes very responsive to conditions in world markets. In the case of the countries mentioned more than twenty per cent of their national income is accounted for by export sales. A high ratio of export revenue to national income is important to the small country from the standpoint of the business cycle. For the sake of brevity we simply term this *cyclical dependence.*

Along with this sensitivity to external demand goes concentration upon a very few commodities for sale in world markets. For example, in New Zealand approximately ninety per cent of export revenue is regularly derived from the overseas sale of four commodities (butter, cheese, meat, and wool) and, for practical purposes, these exports are the product of just two industries. The New Zealand situation is not an unusual one; in fact, other small countries have carried their specialization to the point where overseas income is largely derived from sales of a *single* product. Such extreme degrees of specialization add an element of uncertainty to future prospects. If a new product or process slashes the demand for the small country's export specialty, a serious problem of readjustment can arise. In some instances a substitute export fills the gap, *e.g.*, the case of Chilean copper exports following the 1918 war and an abrupt fall in the demand for nitrates. However, the process of readjustment is not necessarily quick or easy.

It should be noted that the concentration upon a few commodities for sale in world markets is slightly different in its implications from cyclical dependence. Suppose that, in the future, wool-exporting nations will face a serious threat in the form of synthetic substitutes. This need bear no unique relationship to cyclical ups and downs but will be associated with technological change and an altered structure of world trade. Since forces which alter the basic structure of trade in this fashion should be isolated from the cyclical ebb and flow of business activity, the risk of catastrophic changes in the demand for export specialties will be said to involve the threat of *product dependence.*

There is another feature of the small economy's position that deserves emphasis. This third feature goes beyond the economic phenomena of a high ratio of export receipts to national income and a high degree of export specialization. Even if the international economy is not ruled by the law of the jungle, the exercise of national power across political boundaries is not unknown. Small countries have, at times, been at some disadvantage in dealing with their larger neighbors in situations where national power was an end and trading relationships a means to that end. Aggrandizement of power for the large country can involve drawing the small nation within the larger nation's economic orbit, thereby encouraging an integration of the small country with its more powerful neighbor. This integration is likely to leave the smaller country extremely dependent upon a continuance of the relationship, for the very integration of the small country's structure of production with the requirements of its larger trading partner leaves the small country with other alternatives reduced by the exclusive arrangement. In some instances the exclusive arrangements are very obviously instruments of economic warfare and indicative of an economic

penetration of a weaker nation, *e.g.*, Nazi Germany and the Balkan states. In other instances the predatory aspects of the process are absent and the integration of the smaller economy with the larger economy proceeds by mutual choice, *e.g.*, England of the late 19th and early 20th centuries and some members of the British Commonwealth. It is probable that results are a more objective guide than motives or techniques, and any integration of a small nation's economy with that of a larger nation should be considered evidence of *cultural dependence*. The extra-economic emphasis is deliberate, since the effects of this integration are pervasive and do tend to give rise to a measure of cultural penetration whether deliberate or unplanned.

Each of these three types of dependence (cyclical, product, and cultural) is important for the small economy—or is, at least, of potential importance for the small economy. It is probable, however, that no two small countries would be concerned with these types of dependence in the same degree. The category of small nations, including, as it does, countries at such diverse stages of economic development as Belgium and Guatemala, is a broad one. Considerable caution is indicated in applying any conclusions drawn from a general analysis of the small country situation to the position of an individual small nation.

Prior to a discussion of the three types of dependence, a digression of some length is desirable. It must be emphasized that in the digression to follow we shall proceed on the following assumptions:

(a) that cyclical income fluctuations are absent or unimportant,
(b) that risks of specialization are absent,
(c) that the exercise of national power can be ignored since only the pursuit of economic gain by private traders is at issue.

These assumptions simply exclude factors that have previously been classified as involving cyclical, product, and cultural dependence and that are to be considered separately.

The classical and neo-classical theories of international trade paid direct, if fleeting, attention to the position of the small country. The conclusion reached was optimistic in the extreme, since it was held that the small nation trading with a larger partner could actually receive *all* the gain from trade. Such a conclusion might not seem to be compatible with the remarks made here on the dependent and vulnerable position of the small economy. However, the effort here will not be to discredit the conclusion that the small country *may* reap large gains from international trade, but rather to indicate that the theoretical analysis has often been based on restrictive assumptions. Our quarrel is not with the logic of the argument, given its assumptions, but with the universal relevance of the assumptions.

The Small Nation and Gain from Trade

In approaching the "small country case" as it was developed in economic writings of the last century, some historical perspective is essential. Theorists of the classical and neo-classical schools wrote during a period when 19th century liberalism was in the ascendancy. The era of mercantilism with its extensive state regulation of trade was drawing to a close. It was then possible to speak more realistically of foreign trade as involving exchange between very large numbers of private traders operating over, but relatively unhampered by, international boundaries. In this context the classical writers developed a theory of international values that looked to the rational pursuit of self-interest on the part of private traders as the motivating force. Principles of spe-

cialization early viewed as valid for the national economy were extended to the international economy. Specialization in accordance with the dictates of an impersonal market mechanism was viewed as insuring maximum world production. Although the fact is not always understood, the better 19th century writers did not assert that free trade would maximize economic welfare for each country. The correct neo-classical presumption was that non-interference with developing specialization tended to sponsor a world-wide economic allocation of resources.[1] It was never denied (by the more sophisticated) that an individual nation might gain by restrictive practices; but it was held that this gain was at the expense of the nations offended against and, of course, that retaliation could further restrict the benefits of international specialization.

In terms of trade and welfare the pure theory of international trade of the 19th century addressed itself to the related issues of a possible gain from international trade and the division of that gain or surplus among trading nations. The first issue—that of a gain from international trade—was clearly expressed by David Ricardo. It will be recalled that Ricardo's contribution to international value theory stressed the importance of comparative labor costs. The classic example of Portugal and England specializing in wine and cloth production involved gain for both nations, although (in Ricardo's example) Portugal's inputs of labor-time per unit of output were lower in both pursuits. The second issue —that of the division of gain from international trade—was not developed by Ricardo. In the illustration of Portugal and England trading in wine and cloth, Ricardo selected a possible ratio at which the products might be exchanged but did not explain the forces that determined the actual

post-trade barter ratio. Ricardo may have subdued the issue of a division of gain from trade because of the labor theory of value employed in his analysis. In the very first sentence of his chapter on foreign trade Ricardo stated his position in these terms:

> No extension of foreign trade will immediately increase the amount of value in a country, although it will very powerfully contribute to increase the mass of commodities, and therefore the sum of enjoyments.[2]

The labor theory of value upon which Ricardo built was incompatible with a direct increase in value stemming from trade between countries. With labor (and capital) assumed to be mobile domestically and immobile internationally, foreign trade involved not an increase in value measured in terms of labor time but, as Ricardo put it, foreign trade involved an increase in "the mass of commodities and therefore the sum of enjoyments." Thus, for Ricardo, gain from foreign trade would have rested upon a different theory of value from that which he applied to domestic trade, and this, perhaps, explains his seeming lack of interest in the division of subjective gain among nations—or, more properly, division among individuals in the trading nations.

It was left for John Stuart Mill to indicate the factors that determined the actual barter ratio of exchange which would rule in international markets. Mill's contribution was one of explaining the terms upon which trade would be conducted between two countries, *i.e.*, the quantity of home goods that would exchange for foreign goods in an equilibrium situation. Armed with the concept of demand as a schedule of quantities which would be taken at various barter ratios, Mill suggested that the precise terms upon which trade would be conducted depended upon the character of each country's demand for the goods of the other. While it was

left for Alfred Marshall to provide geometrical embellishments and stability conditions for an unique equilibrium,[3] Mill's contribution was substantial.

The stress laid upon reciprocal demands in Mill's analysis represented a shift away from the Ricardian emphasis upon comparative labor costs. Modern treatments of the theory of international prices proceed in a general equilibrium framework and would not accord independent influence to either demand or cost factors. But so long as the analysis ran in terms of *constant* comparative costs and reciprocal demands, it was possible for 19th century theorists to subordinate the influence of cost factors. It could then be asserted that the influence of comparative costs was exhausted in setting the limits to profitable exchange and that forces of demand determined the barter ratio of exchange and the division of gain from trade. Such a treatment can reduce the problem of international values to an equivalent level with that of exchange between two individuals each of whom possesses beginning stocks of two commodities and barters so as to achieve a most desired consumption menu. The unsatisfactory nature of this treatment did not escape the notice of later 19th century theorists. The case of a small country trading with a larger country was adduced as a special case where the forces of reciprocal demand were ineffective in setting the barter ratio.[4]

With the opening of trade between two countries of similar productive capacity any difference in comparative costs would commence a shift of resources in each country into the line of comparative advantage. If this resource diversion were to continue until each of the nations was *completely* specialized, reciprocal demands would determine the barter ratio between the nations. Complete and simultaneous spe-

cialization would allow the problem to be reduced to one of pure exchange. But if one country were large and the other small, the small nation could become completely specialized while the larger nation produced some of both commodities (in a two-country model). This would involve the small nation trading *at* the cost limit of its larger neighbor and achieving *all* the gain from trade. In this special case the large nation achieves no gain since its consumption menu is the same before and after trade. The only changes in the large country occur on the side of production. More of one commodity and less of another will be produced at home. Consumption is unchanged.

A geometrical treatment may emphasize the failure of reciprocal demands to set the terms of trade in the special case of trade between a small country and a large one.[5] Some preliminary steps are unavoidable. First the technique will be applied to the "normal" case of trade between countries of similar size. Adhering to Mill's assumptions of bilateral trade in only two commodities, it is assumed that two countries of similar size (A and B) produce two commodities (X and Y) at constant cost. Suppose that the relative costs of producing X and Y at home differ as between country A and country B. In such a case trade is possible and will encourage specialization in each country upon one of the commodities. It is further assumed that country A is relatively more efficient in the production of X while country B's advantage lies in the production of Y. Figure I pictures such a situation. Amounts of X goods that will be exported by country A at various barter ratios are measured along the horizontal axis. Amounts of Y goods that will be exported by country B at various barter ratios are measured along the vertical axis. The slopes of OCF and ODE represent the (constant) cost

ratios of production for commodities X and Y in countries A and B respectively. The reciprocal demand schedules (ODG and OCH) for each country are linear to the amount of pre-trade production (and consumption) of commodity Y for country A and commodity X for country B. This construction allows for the possibility that the countries would be indifferent between home and foreign sources of supply (ignor-

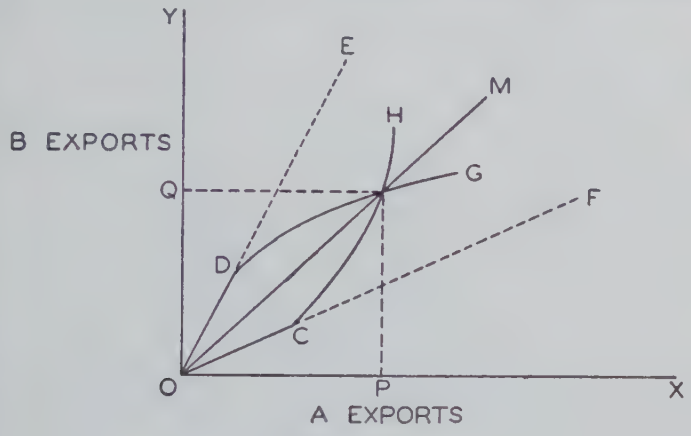


FIGURE I

ing costs of transport) at the pre-trade barter ratio.[6] When this critical point is passed the reciprocal demand schedules are curvilinear.

As drawn, Figure I implies a unique equilibrium with OP of A goods exchanged for OQ of B goods. The one barter ratio which will clear the market is given by the slope of the line OM to the intersection of the reciprocal demand schedules ODG and OCH. In terms of Figure I the (constant) cost ratios for the countries (ODE and OCF) define a region within which possible barter ratios must lie; and the shape of the reciprocal demand schedules (ODG and OCH) determines the equilibrium terms of exchange. Ricardo would have

suggested that trade would take place at *some* barter ratio between the cost limits. Mill suggested that *the* ratio would be determined by the forces of reciprocal demand.

The case of a small nation trading with a large nation may be handled in the same fashion. The only change is one of pre-trade productive capacity. In Figure II the linear segments of the reciprocal demand schedules (coincident with

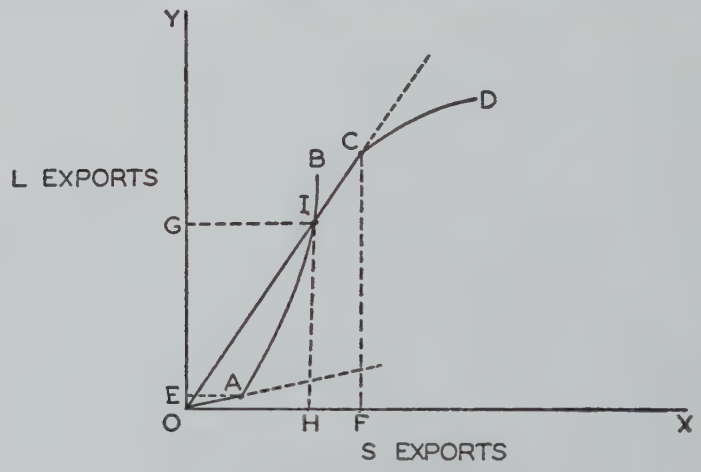


FIGURE II

the domestic cost ratios) have been constructed so as to be of unequal length. The large country (L) is equipped with a linear segment OC implying OF of X as pre-trade home production (and consumption) of that commodity. The small country (S) is equipped with a linear segment OA implying OE of Y as pre-trade home production (and consumption) of that commodity. The curvilinear segments AB and CD are once again based upon individual preferences in countries S and L respectively. As drawn, Figure II implies a unique equilibrium at point I with OG of L exports of commodity Y exchanging for OH of S exports of commodity X. In this

special case the post-trade barter ratio and the pre-trade cost ratio in country L are identical in equilibrium. Experimentation with barter ratios drawn clockwise from OC will reveal that no other barter ratio will equate the offers of the two countries.

Now the alleged failure of reciprocal demands to determine the equilibrium barter ratio in the small country case

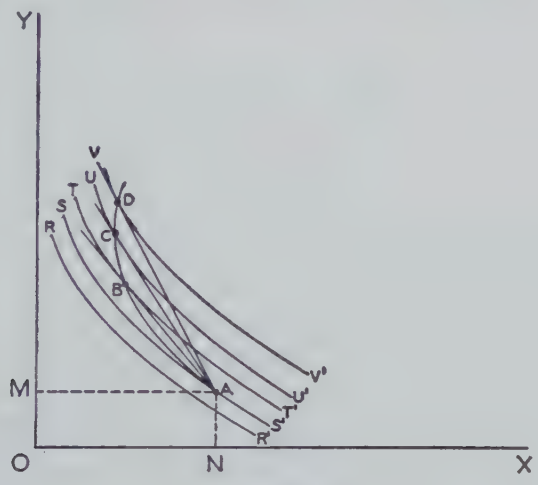


FIGURE III

may be examined. Superficially it appears that the treatment in Figure II differs in no very important respect from that of Figure I. However, in drawing the schedules with a linear segment, implicit account has been taken of changes on the side of production. In order to isolate the influence of demand, a case of pure exchange[7] will be considered for trade between two countries of similar size and for the special case of trade between a large and a small nation.

The derivation of the reciprocal demand schedules or offer curves can be described briefly. In Figure III which applies to one of the countries, amounts of commodity X are

measured along the abscissa and amounts of commodity Y are measured along the ordinate. A family of contour lines is drawn in the XY plane. These contours are subject to the following interpretation. The community is said to be indifferent to any combination of commodities along a single contour line, say, RR'. A position upon any higher contour involves a movement to a more preferred position.[8] The community possesses a beginning stock of commodities X and Y. In Figure III, point A on contour SS' is the community's original position—a stock composed of OM of Y and ON of X. With the opportunity for exchange the community is faced with different barter ratios of exchange. These different trading ratios are described by a family of lines pivoting on point A. As the exchange lines pivot in a clockwise direction (a relative fall in the price of Y) the community may move to a more preferred position. With a given price ratio, tangency of an exchange line with a contour insures that the most preferred position has been achieved. Successive barter ratios trace out a series of these points (A, B, C, and D of Figure III).[9] The offer curve for the community is simply the locus of all possible points of tangency. A smooth curve has been drawn through points A, B, C, and D of Figure III implying successive tangencies with undrawn contours.

A similar interpretation may be given to the offer curve for the other country.[10] Now with both offer curves derived, they can be plotted on a single set of coordinates. Figure IV sets out two conventionally-shaped offer curves for countries of similar size. The diagram only differs from that of Figure I in that offer curves for both countries (in Figure IV) are curvilinear from the origin.[11] Suppose that an attempt were made to parallel the treatment of Figure IV in the case where both countries are not of equal size. Instead of a diagram similar to

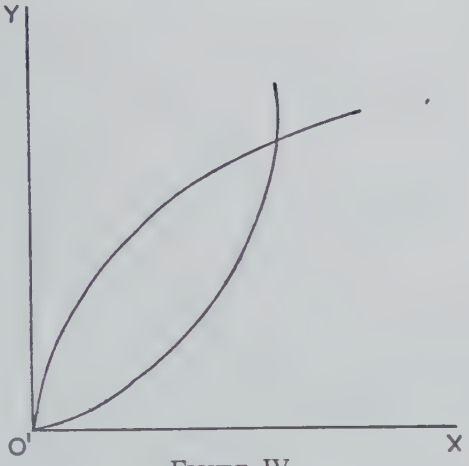


FIGURE IV

that of Figure IV, it is clear that only the small country's offer curve could be derived. The large country's offer curve degenerates to a single point—the origin—representing the consumption menu before and after trade in the large country. It is true that the *shape* of the small country's offer curve determines the degree of specialization in the large country; but *if* the small country case is involved the barter ratio of exchange is set independently of the influence of demand.

The "failure" of reciprocal demand analysis in the small country case was, of course, symptomatic of the inadequacy of any approach to international values more restrictive than one of general equilibrium. It is beyond the scope of the present discussion to indicate successive refinements in the neoclassical position, *e.g.*, the extension of the analysis to trade between many countries in many commodities and the abandonment of the unrealistic constant cost assumption.[12] Instead it is proposed that an effort be made to summarize briefly the conditions required for large gains by small nations.

Gains from trade stem from the opportunity for exchange in the face of relative price differences at home and abroad. Ignoring transport costs, trade establishes in equilibrium a new, common set of relative prices. Large gains for the small nation are contingent upon two factors. First, the small nation must find the post-trade equilibrium relative price set coincident with (or very close to) that which would rule if the small nation did not, in fact, trade with the rest of the world. If a large, previously isolated, nation were to open trade with the rest of the world, it would likely exert a substantial effect upon relative prices. But the small nation may be favorably situated because of its insignificance. The limiting case is simply one where the small nation's influence on relative prices is literally zero and where all gain accrues to the small nation.[13] There is, however, a second factor upon which a large gain by the small nation is contingent. While a minor influence upon relative prices is necessary for a large gain, it is not sufficient. For example, the small nation might be as small as one likes, but if its set of relative prices in the absence of trade happened to coincide with the set ruling in the rest of the world, no trade would be possible and, of course, no gain from trade would result. A large gain requires a wide divergence between relative prices at home and abroad (without trade) in addition to the privilege of trading at world prices without disturbing them in appreciable fashion.

It is tempting to reduce the divergence of relative prices to one of differences in factor endowment and production possibilities. Then it could be said that the small country with very skewed resources is likely to achieve the most substantial gains. One difficulty is involved since this conclusion rests upon an implicit assumption as to a degree of similarity in tastes and preferences between countries. A small nation

might be prodigiously efficient in the cultivation of bananas, but capable of little else in the way of efficient production. Should the preferences of the community subscribe to a rather monotonous consumption menu, it is possible that no very profitable avenues for gain through international trade would exist. But should the community's tastes extend to washing machines and radios, it is likely that international trade would involve very substantial gains.

The conclusion that small countries are large gainers is, after all, most convincing when one reflects that the small nation tends to achieve through international trade what a more sizable nation would very largely achieve through interregional trade. Specialization upon a narrow range of products for exchange in world markets enables individuals in the small nation to enjoy a diversified consumption menu. It will now be contended here, however, that there are peculiarities in the small-country position that require some discounting of these *potential* gains.

Cyclical Dependence

This section will concentrate upon the small-country position in a world economy that experiences fluctuations in income and output. Fluctuations in income and output do occur and a very modest development of the small-country position will be sufficient to establish that these disturbances are of particular importance for the small nation. It has been suggested that a high ratio of export revenue to national income is indicative of cyclical dependence. At the very least cyclical dependence carries with it two undesirable effects. These are: first, a very high degree of sensitivity to income fluctuations external to the home economy; and, second, a very low degree of freedom with respect to domestic policy

measures designed to offset externally-induced income movements. The discussion to follow develops these propositions and indicates their relevance for the small country.

Some preliminary attention must be given to the international transmission of income fluctuations. The treatment will be perfunctory and no distinction will be drawn between real and money income. From the standpoint of income determination, an open economy differs from a closed one in that some part of expenditure upon home-produced goods and services, and hence some part of home income, does not arise domestically. In the open economy a stream of expenditures upon export goods comes from abroad. Consequently, home exports are a function of foreign income. The other link with the outside world is, of course, the stream of home expenditures that is directed upon foreign goods. Imports are a function of home income. Any open economy finds that home income depends upon foreign income through the channel of export sales, and correspondingly that some influence is exerted upon foreign income through the channel of import purchases. Suppose that home income has found a steady level and then that foreign incomes fall. Initially at home only export sales and exporters' incomes will suffer, but the income decline will filter through the domestic economy as expenditures and incomes are reduced. It can be shown that with a given fall in foreign income, and therefore in export sales, home income will usually find a new (but lower) level. In other words, the foreign-induced decline in home income does not continue forever, but is braked by factors that arrest the cumulative decline. These "braking factors" are induced reductions in savings and in import purchases.

Let us take the first undesirable feature of cyclical de-

pendence, *i.e.*, a high degree of sensitivity to income movements external to the home economy. A decline in foreign income is postulated. If countries were of similar size and foreign trade were of equivalent importance to each country, then *absolute* changes in income would be of interest. But in the more general case, it is obvious that relative changes in income must be used, *i.e.*, a ten per cent fall in home income rather than a fall of "x" million francs. The relative fall in home income for a given change in foreign income can be shown to depend upon these effects:

1. The percentage cut in home exports caused by a given percentage fall in foreign income.
2. The percentage fall in home income that results from the percentage fall in home exports.

If the small nation actually does tend to show a higher sensitivity of home income to changes in foreign income, the reason is to be found in one, or both, of these two effects. The reason is not to be found in the first effect. At constant prices, the percentage fall in home exports will simply depend upon the foreign income elasticity of demand for imports from the small country. It is quite true that *some* small countries are unfavorably situated because of the type of exports they sell in world markets. In times of depression, Ceylon may experience a more sizable decline in export revenue than will New Zealand; but cyclical sensitivity of exports is not the exclusive property of small nations. Small countries will differ among themselves in sensitivity to foreign income changes, but we are in search of a factor which explains greater sensitivity for small nations than for large nations.

The unique feature of the small-country position is to be found in the fact that, given a percentage fall in export receipts (not uniform for all small countries with a given change in world income), pressures are set up for a very sizable per-

centage fall in home income. The argument can be condensed somewhat if we introduce the following symbols:

Let Y = the beginning level of home income,

and E = the beginning level of home export sales.

Then $\frac{\Delta Y}{Y}$ and $\frac{\Delta E}{E}$ may stand for the percentage change in home income and exports. Whatever the quantitative relationship between these changes, it is possible to write $\frac{\Delta Y}{Y} = \alpha \frac{\Delta E}{E}$ where "α" simply insures the equality. In this form the equation is a truism. Any tendency for the small nation to experience a large percentage change in home income for a *given* percentage change in exports must occasion a large coefficient (α). This is not helpful unless α can be expressed in familiar terms. A rearrangement of the expression yields $\alpha = \frac{\Delta Y}{\Delta E} \cdot \frac{E}{Y}$. In this form α is seen to depend upon the multiplier for a foreign induced change in export receipts, and the beginning ratio of exports to home income.[14] The second factor $\frac{E}{Y}$ is sure to be large for the small country.

In suggesting at the beginning of this paper that a high ratio of export proceeds to home income was indicative of cyclical dependence, no attention was given to the probable size of the multiplier term for the small country. Actually a moderately low multiplier might be expected on the grounds that the quantitative size of the multiplier depends inversely upon the marginal propensities to save and to import. The small country will typically increase or reduce its import outlay substantially with a given change in income, *i.e.*, the marginal propensity to import will be high. No dogmatic

judgment can safely be expressed as to the probable size of the marginal propensity to save as between large countries and small. Probably the stage of economic development is a greater determining factor than the size of a country in this connection. It would seem, then, that the two terms (the multiplier and export-income ratio) work in opposite directions for the small country. We may be sure, however, that the range of variation for the multiplier will be fairly narrow. Consequently it is the large export-income ratio, in the case of the small country, that is conducive to the magnification of any fluctuation in external demand.

The second undesirable feature of cyclical dependence is simply that the small nation is severely handicapped in its efforts to avoid the full impact of changes in external demand. It is clear that world-wide income movements are not generated in the small country. The small country may experience the widest extremes of prosperity and depression without more than incidental disturbance to the rest of the world. Any income fluctuation in major trading countries, on the other hand, will exert a large effect upon the small nation. A reasonable proposal might be that the small nation should attempt to offset some of the deflationary (or inflationary) pressure from abroad through domestic policy measures. But notice that the small-country position is one in which any change in domestic expenditure is very quickly and sizably reflected into its external accounts. The small nation that undertakes an extensive program of public expenditure in a depression will find that a considerable amount of this expenditure leaks away in the form of increased imports from the rest of the world. As one writer has put the matter, "It is trying to heat the house in winter when one is unable to close the doors and windows."[15] The analogy is

an entirely proper one, for the benefit derived by the rest of the world is insignificant. The appropriate remedy is quite apparent. The major trading nations that have suffered income declines and developed "favorable" balances of payments should take steps to increase the level of home expenditures. As home incomes increase, purchases from abroad increase, wiping out the trade deficits abroad and raising incomes abroad. The large nation may cast its bread upon the waters with some confidence since the repercussive effects will be beneficial as foreign incomes rise. The ability of the small nation to inflate the rest of the world is, of course, negligible. In a stable international economy these effects would be unimportant, and "the more sinned against" interpretation of the small country's lot would be improper. But in an international economy in which the transmission of depression and inflation is common, the small country may see merit in policies that reduce its degree of cyclical dependence, even though the policy measures involve some sacrifice of the undoubted gains of international specilization.

Product Dependence

International trade theory suggests that gains from trade may be greatest where a very few export commodities exchange for a much wider range of imported items. It will be recalled that the "small-country case" involved the small country *completely* specialized. With the extension of the analysis to the case of multilateral trade in many commodities, the likelihood is lessened that the small country will specialize to the extent of concentrating upon a single export, but the probability is not removed that where the small nation achieves large gains it does so by exporting a

very narrow range of items, perhaps even a single product. In the theoretical literature, references to the gains from specialization are far more common than references to the risks and uncertainties involved. This is understandable but should not lead one to conclude that, in reality, the risks of specialization are non-existent. While the case for specialization to achieve high levels of real income is a strong one, it should not receive unquestioned application.

Specialization involves resource allocation in accordance with a set of relative prices. Where the relative prices are determined competitively, there is some justification for presuming that an economic allocation of resources has been achieved. For the small nation the allocation may be very largely determined by a *given* set of world prices. The question immediately arises as to whether the small nation might not become "artificially specialized" where it traded at a set of relative prices which, far from being determined impersonally, were set by a more powerful nation (or group of nations) for the express purpose of inducing in the small nation an allocation of resources that would contribute to the power potential of the larger entity, *e.g.*, fostering a dependent nation's specialization upon critical raw materials through the medium of very favorable terms of trade. The possibility is not too remote for consideration, but is more properly treated in the discussion of cultural dependence. For now it will be assumed that whatever specialization is induced in the small nation by international trade, that specialization results from economic forces.

Given a set of world relative prices external to the small economy, international trade will effect a certain distribution of small-country resources after trade. This resource allocation is likely to involve a much higher degree of export spe-

cialization in the small economy than would be involved in the case of a larger nation. From a purely static point of view this specialization need be of no particular concern since small-country concentration upon a very few export commodities is evidence of large gains from trade. It is worthy of note, however, that a high degree of specialization and large gains from trade can mean a large loss from the interruption or disturbance of trade. Along these lines it has been pointed out that gain from trade could even serve as a measure of the influence that might be exerted upon a small nation.[16] This view is a useful one where considerations of national power are relevant. The view can also be applied where the exercise of national power is not at issue but where economic risk and uncertainty are involved. In such a case a large gain from trade implying a large loss from its interruption testifies to the vulnerability of the small nation to any changes in relative prices that affect its own export specialties in drastic fashion. Such a change might arise from the side of demand in the form of a shift in consumer preferences, or such a change might arise from the side of supply in the form of a new product or process competitive with the small country's exports. In any event the small nation is faced (as are other nations) with the probability that once a certain degree of export specialization is achieved at home under the direction of relative prices, some future change in the basic data that determined the equilibrium price set will compel a change in the allocation of domestic resources.

Now the prospect of adaptation to change can, under certain circumstances, be an unattractive one. It will be urged that the position of the small country is such that some attention must inevitably be given to possible future changes in demand or supply that would require either a sharp fall in

real income, or a resource shift of large magnitude, or some combination of both. One point must be stressed. From the standpoint of comparative statics, *i.e.*, the comparison of two equilibrium positions, one before and the other after a change in the basic data, the adaptations on the part of the small nation are necessary and unavoidable if an economic allocation of resources is to be achieved and maintained. Our point is simply that the small country should be particularly interested in the probable course of adjustment and in the prospect for policy measures designed to ease transitional adjustments.

The threat to small-country real income is made acute by two factors. First, concentration upon a few exports means that a sharp decline in the price of an exported item will initially occasion a substantial fall in real income. For present purposes the argument will not depend upon the susceptibility of certain exports to competition,[17] but will be made to rest upon a much simpler proposition. Fewness of exports coupled with a high ratio of export revenue to national income insures that decreased revenue from a single export commodity initially involves a substantial reduction in home income.[18] For example, suppose that a small country exports only two commodities, perhaps copper and wheat, but that the ratio of export revenue to national income is high, say thirty per cent. Another larger country exports ten commodities (copper, wheat, and eight others), but the ratio of export revenue to national income is low, say ten per cent. A sharp fall in world demand for wheat (or copper) will face the small nation with a much more substantial fall in real income than it would for the large nation. The small nation's degree of external orientation renders it very susceptible to changes in world demand (or supply). On the other hand,

a larger (more diversified) economy can more easily tolerate a reduction in home income from displacement of a single export since the effect upon domestic standards of living will be of smaller proportions.

The second factor arising from a high degree of export specialization is not limited to the initial impact of a change in the conditions of world demand and supply, but refers to the possible resource shifts that follow the collapse of an external market and make possible the achievement of a new equilibrium position. The small-country problem is one of limited alternatives and a low degree of resource mobility.

For the sake of illustration, let us take the extreme case of a small nation which, when faced with a certain set of relative prices, has specialized to the extent of producing a single commodity for export and sale in world markets. Naturally some other commodities and services will still be produced at home since at any set of relative prices there are items that will not move at all readily in international commerce, *e.g.*, cement and haircuts. But, by and large, the small country's structure of production will reflect its export specialization with a considerable number of domestic industries ancillary to the export industry. Now, if one takes the gloomiest view possible and presumes that world demand for the export specialty is completely wiped out, real income for the small country will not only suffer a very drastic cut but will stay at low levels for some length of time. The very degree of export specialization is likely to have encouraged the development of specialized skills, techniques, and equipment.[19] Where factors of production are quite specific, it may be expected that sharp falls in their return will leave them stranded. The point is that the single-product economy will in complete specialization have reduced its

own alternatives. Faced with the necessity of shifting resources to alternative pursuits, the small country may find that feasible alternatives are not immediately available.

The net effect of the fact that small-nation income is bound up with the fortunes of a few exports and that the domestic possibilities of shifting resources to new pursuits may be limited by that concentration in a few lines, is that the small country's real income is liable to wide fluctuations.[20] It is essential to note that the static gains from trade concept implies small-country achievement of a high level of real income through foreign trade. The substance of our qualifying remarks is that a high degree of product dependence implies the possibility of a high but widely fluctuating real income. Let us dispose of one point in summary fashion. If one small-country alternative is non-interference with specialization, another is the cessation of trade and the complete "insulation" of the home economy. It is presumed that the latter alternative is not a practical or desirable one. But, there are no grounds for assuming that the community will desire the maximum level of real income available through specialization *regardless* of possible fluctuations around that level.

If it is granted that the small-country choice may be for future incomes that are liable to essentially unpredictable fluctuation, considerable light is thrown upon the role of policy measures in the small country. There is no possibility of an actuarial approach to the future for domestic authorities. Product dependence involves uncertainty as to future world demand and, at best, only educated guesses can be made as to the wisdom of, say, diversifying the home economy *now* in anticipation of a fall in world demand at some time in the future. It would seem that desirable policy meas-

ures should aim at increasing the mobility of domestic resources and encouraging the development of alternatives in anticipation of any severe change in the world demand for export specialties. Neither of these objectives is necessarily achieved through the impersonal operation of the price system.

The present discussion cannot include detailed evaluation of specific policy measures in small-country situations. It must be evident, however, that the conclusions of static analysis, *e.g.*, large gains for small countries, cannot be taken to apply without exception in a context of uncertainty. Consequently, the task for policy-framers in the small country is one of anticipating risk and uncertainty without renouncing the gains of specialization. The problem is not a simple one, nor is it insoluble.

Cultural Dependence

The discussion of cyclical and product dependence referred to economic effects. In turning to the concept of cultural dependence, it is not possible or desirable to confine the discussion within such narrow bounds, although it will be advisable to concentrate upon economic aspects of the problem. Even so it is not possible here to do more than to indicate the importance of cultural dependence for the small nation, since an adequate development of the phenomenon would require lengthy and detailed analysis.

At an earlier stage it was suggested that cultural dependence was evidenced by the "integration" of one nation's economy with that of another. International trade always gives rise to a mutual adaptation of productive structures.[21] With the introduction of trade a re-allocation of resources is sponsored at home and abroad. Little reflection is necessary

to convince one that, historically, trade has also had an impact upon individual preferences. There are advantages in considering *any* trade between countries as involving a measure of cultural dependence. All that is implied is that with trade, economic activity in separate countries becomes to some degree interdependent, and that this economic interdependence will almost inevitably involve the nations in an interdependence extending to non-economic relationships.

Cultural dependence may be viewed as a thoroughly desirable by-product of international trade. No doubt a considerable part of the appeal of free trade arguments rested upon the debatable presumption that the prosecution of individual interest would necessarily lead to a cosmopolitan atmosphere conducive to the relaxation of international tensions. This view may be, and has been, presented in such uncompromising style as to leave one suspicious that only an over-simplified view of the world economy could yield such a conclusion. Still it would not be defensible to urge that cultural dependence is undesirable *per se,* for such a position would imply that international trade is either undesirable itself, or else that its advantages are subject to reduction to the extent that any cultural dependence is involved. The fact of the matter is that cultural dependence may or may not be desirable depending upon the particular type of trading relationship which is associated with it. The distinction may seem pedantic and non-operational in that cultural dependence apparently can be one thing at one time and place and another thing at a different time and place. That, however, is precisely what we mean to contend. Any alternative view forces one to conclude either (a) trade always can yield desirable results, or (b) trade never (rarely) yields desirable results. Unless one feels that the followers

of the Manchester School or the followers of Rosa Luxembourg have presented a well-rounded appraisal, some position between the extremes is necessary.

Let us return to the position of the small economy, bearing in mind the view that while cultural dependence (or interdependence) is associated with trade, cultural dependence may or may not be viewed as desirable according to specific circumstances. Upon several occasions it has been emphasized that the small country trading internationally achieves a very high degree of specialization. This economic effect will, we now urge, typically involve a substantial degree of cultural dependence. There can be no argument but that a high degree of specialization involves dependence; this should be amply clear from the earlier discussion of cyclical and product dependence. But is it inevitable that the small country's *cultural dependence* will be of a higher degree than that of a larger nation? It is not inevitable that such should be the case, but there is a strong presumption that it may be.

Let us take the case, once again, of a hypothetical small country that has specialized to the extent of concentrating upon a single export for sale in world markets. It is conceivable that this very specialization may operate *against* the development of cultural dependence. It could do so where the specialization of production gives rise to economic, political, and social institutions peculiarly adapted to conditions of production. This possibility is lessened to the extent that the wide range of small-country imports tends to break down specialized institutional arrangements and to establish in their place arrangements modeled after those of larger and more diversified nations. The problem is often one of economic development. While extreme degrees of domestic specialization may work to establish certain cultural patterns,

forces are set up which in turn tend to break down these patterns. Historically it is possible to observe the co-existence of the new with the old, *e.g.*, Japan of the late 19th and early 20th centuries and many nations presently in the process of rapid development. The hypothesis is one which cannot be elaborated at this time. It will be noticed that it would move away from the concept of size and substitute in its stead a concept of stages in economic development.

Let us return once more to the "pure" small-country situation. The feature of the small-country position to which we wish to direct attention is that of the small nation trading in a world economy in which the exercise of national power is important. While we would not deny that cultural dependence would exist in the absence of the maximization of power positions, it is felt that cultural dependence is of somewhat more interest in the case where nations trade for non-economic as well as economic motives. It is taken for granted that, upon occasion, political units do conduct their trade on other than economic grounds. Whether or not they *should* do so is a question upon which no judgment will be expressed.

The implications for the small country trading in situations where national power is involved are quite clear. In such a case the large gains of small nations are symptomatic of a weak position from a power standpoint.[22] This is apparent when it is appreciated that the large (powerful) nation evaluates trade not only upon its economic merits but also upon its non-economic merits. The larger nation has, broadly speaking, two courses of action open to it. In the first place, the large nation may increase the gains to the small country by offering the small country better terms than an impersonal market mechanism would offer. In this case it might be ob-

served that the large country pays for value received. In the second place, the large country may threaten the small country with an interruption of trade. In this case the large country may not have to pay for value received. The weakness of the small-country situation is emphasized when it is realized that the large country may pursue *both* courses of action although not simultaneously with respect to a single small country. That is to say, the large country may first, if necessary, encourage the small country's dependence, and subsequently, with small-country alternatives reduced, proceed to exact a much harsher bargain. Where the large nation is fortunate enough (from a Machiavellian standpoint) to be able to face a number of small countries with "all or none" offers, the situation is akin to that of a single, discriminating purchaser in an imperfect market. It is hardly necessary to add that the stakes are rather higher than in a purely economic setting.

It may be questioned whether or not the small-country lot is quite so unfavorable. Is it not possible that the small country will be strategically located from a power standpoint by virtue of the importance of its specialty? This could, perhaps, allow the small nation some latitude in avoiding a very subservient role. Three comments may be made. First, the critical product must be one not available from alternative suppliers so the small-country advantage is unique. Second, the product must not be *so* critical as to expose the small country to direct rather than devious pressure. Third, the small country must not be caught between a few more powerful nations. Such an equilibrium would be precarious and likely to force the small nation to "throw in" eventually with one or another of the power blocs.

Particular interest is attached to the small-country situa-

tion where national power is at stake. In such an event, the exercise of national power by the large nation is capable of sponsoring cultural dependence of an extreme sort. This cultural dependence amounts to a calculated penetration of a weaker nation by a stronger one and, perhaps, is at one and the same time more readily evident than the more subtle process by which cultural dependence arises in the absence of the power struggle and more destructive of the existence of the small nation as an independent entity. Cyclical and product dependence may actually be of minor importance in such a setting in which individuals in the small country might look back nostalgically to a time when only economic risk was to be feared.

Conclusion

The perfectly proper emphasis given in economic theory to the *possibility* of large gains by small nations requires careful interpretation in realistic situations. Some doubt has even been raised in our analysis as to the usefulness of a concept of size. Attention has been directed here to the small-country situation because of the special treatment accorded to trade between a large country and a small one in the 19th century version of international trade theory.

Actually the concepts of cyclical, product, and cultural dependence are of service in other situations. The concepts of dependence can be applied in the international economy where nations differ not in "size" but in stage of economic development. Nor is the application limited to the international economy. With some modification these same types of dependence are faced by separate regional economies within a single nation.

John H. Auten

NOTES

1. Whether or not the resource allocation with unimpeded specialization would achieve an optimal distribution of real income among countries depends upon: (a) the "beginning" distribution of income, and (b) the non-economic criterion of an optimum distribution that is selected.
2. David Ricardo, *The Principles of Political Economy and Taxation,* Sraffa Edition (Cambridge, 1951), Vol. I, p. 128.
3. Mill attempted a consideration of stability conditions. See his *Principles of Political Economy,* Peoples Edition (London, 1886), pp. 360-365. The effort was prompted by Thornton's criticism that more than one exchange ratio might clear the market. Mill's treatment of this minor issue was faulty.
4. For a view as to the origins and significance of the small-country case see Jacob Viner's *Studies in the Theory of International Trade* (New York, 1937), especially pp. 448-450. A rather less charitable interpretation of neo-classical understanding of the implications of partial specialization is expressed in F. D. Graham's *The Theory of International Values* (Princeton, 1948), especially Chapters II and XI.
5. The reader who is prepared to accept the failure of reciprocal demand in the small-country case may prefer to proceed directly to the second paragraph on p. 13. The intervening discussion is not vital to the conclusions of this section.
6. On this point, see Viner, *Studies,* p. 547, and T. M. Whiten, "Classical Theory, Graham's Theory, and Linear Programming in International Trade," *Quarterly Journal of Economics,* Vol. LXVII (November, 1953), p. 528.
7. Pure exchange refers to a situation in which production is not involved.
8. This particular interpretation is a proper one only for the case of a single individual, *e.g.,* an "average Englishman." When contours of indifference as between commodities are constructed for a community composed of many valuing individuals, important difficulties are obscured. Any point in the XY plane will involve some distribution of the commodity stock among community members. Conceptually one should allow for the fact that there is not one but an infinite number of contours passing through this point in order to take account of all conceivable distributions of the commodity stock. The difficulty may be expressed in a slightly different fashion. Suppose that the community commences trade and moves from its original position to one on a higher indifference contour. Is the community better off? It would be (almost) inconceivable that every individual regarded himself as being better off. Typically, trade will involve a different distribution of income than no-trade

with some individuals gaining and others losing. Ways can be found out of this impasse but will not be detailed here. The interested reader is referred to: T. deScitovszky, "A Reconsideration of the Theory of Tariffs," *Review of Economic Studies*, Vol. IX, 1942, pp. 89-110; P. A. Samuelson, "The Gains from International Trade," *Canadian Journal of Economics and Political Science*, Vol. V, pp. 195-205; I. M. D. Little, *A Critique of Welfare Economics* (Oxford, 1950), Ch. XIII. The deScitovszky and Samuelson articles are reprinted (without significant change) in *Readings in the Theory of International Trade* (Philadelphia, 1949).

9. Rotation in a counter-clockwise direction traces out another branch of the offer curve. Only the branch drawn is needed for present purposes.
10. The geometry will be subdued. The relevant branch of the offer curve would extend down and to the right rather than up and to the left as in Figure III.
11. In the case of Figure IV the origin is taken as the beginning commodity stocks in each country. Each country could have possessed an initial stock of only one commodity without affecting our conclusions.
12. The reader interested in the historical development of international trade theory is referred to Viner, *Studies*. A valuable summary of the current status of international trade theory is contained in Lloyd Metzler's "The Theory of International Trade," in *A Survey of Contemporary Economics*, H. Ellis (editor), (Philadelphia, 1949), pp. 210-254.
13. Interestingly enough this is the one case where the impossibility of deriving a thoroughly satisfactory index of gain from trade is of no particular concern.
14. The reader not familiar with the multiplier concept for an open economy will find a lucid treatment in C. P. Kindleberger, *International Economics* (Homewood, Illinois: Irwin, 1953), Ch. 9.
15. Kindleberger, *op. cit.*, p. 169.
16. A. O. Hirschman, *National Power and the Structure of Foreign Trade* (Berkeley, 1945), p. 18.
17. A peculiar type of "competition" to which certain exports are likely to be susceptible does deserve mention. The small country that specializes in exports having a low income elasticity of demand (*e.g.*, staple foodstuffs) may expect to lose relatively as world real incomes rise. In this case competition comes from goods and services of higher income elasticity as foreign consumers achieve higher standards of living. For the small country, the advisability of hastening resource transfer out of low income elasticity lines (certain agricultural pursuits) can be modified if the *short run* terms of trade are expected to be very favorable.

18. The statement assumes that revenues from each export commodity represent a substantial portion of total export revenue.
19. This effect will vary according to the type of export. It would not change the argument if export specialization prevented (hindered) the domestic development of a trained labor force and more than the rudiments of a capital market.
20. The discussion here has run in terms of cuts in real income. It could be modified to allow for inflationary impacts from abroad.
21. This is even true in the theoretical case of trade between two nations with equal relative (but variable) costs of production where trade occurs on the basis of differences in tastes. See W. W. Leontief, "The Use of Indifference Curves in the Analysis of Foreign Trade," *Readings in the Theory of International Trade* (Philadelphia, 1949), pp. 234-235.
22. See Hirschman, *loc. cit.* and pp. 23-33.

COSTS OF OPERATING CRUDE OIL PIPE LINES*

I. Production Function

THE procedures of economic production function analysis may be used to simplify the problems arising in the design of crude oil (or other) pipe lines. In the designing of oil pipe lines there may be said to be five principal physical variables present: (1) line diameter, (2) horsepower, (3) safety factor, (4) wall thickness, and (5) operating pressure. A given throughput may be achieved by the use of any of several available line sizes (outside diameters), each of which is also available in several inside diameters (or wall thicknesses). This throughput may be obtained for any given pipe size by the use of any of many possible operating pressures to produce the required horsepower; low pressures mean more stations, while high pressures mean fewer stations. A maximum pressure is set by the safety factor and pipe strength, but the safety factor may be varied (and is) within fairly wide limits.

The basic question to be determined in any pipe line design problem is this: what is the cheapest combination of these variables—line diameter, horsepower, wall thickness,

* This paper is a report of the methods and findings of an empirical cost study of the crude oil pipe line industry. The capital costs were originally computed by the author and Mr. Alan F. Rhodes for the recent Rice Institute Petroleum Research Project, which was carried out for the Air Force and the Bureau of Mines. These costs were revised and combined with annual operating costs as part of the author's doctoral thesis in the Department of Economics and Social Science at the Massachusetts Institute of Technology. The author expresses his indebtedness to the following in addition to Mr. Rhodes: Dean Edward S. Mason, Professor M. A. Adelman, Professor J. E. Hodges and the staff of the Rice Petroleum Project, Dr. F. T. Moore, and the School of Industrial Management at M.I.T., which generously provided a grant for a summer spent in revising the thesis.

the ordinate and C is the abscissa (see Fig. 1), the L intercept of each line is $\frac{E}{P_L}$. Of any two lines in the family, the one having the higher intercept of the L axis will represent a higher total expenditure.[3] Since it has the greater intercept it will lie farther from the origin. Consequently, it may be said that expenditure lines lying away from the origin represent higher expenditures than those lying near the origin.

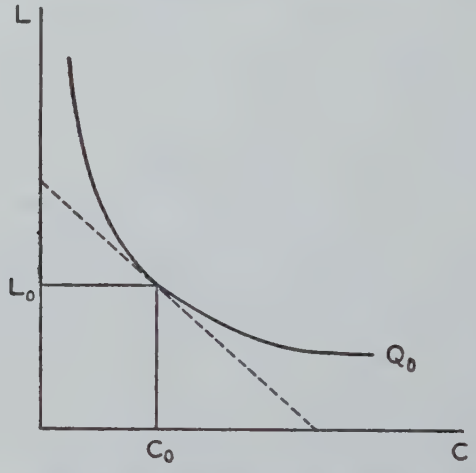


Fig. 2. Optimum Combination of Two Factors of Production.

The physical relationship between L and C for the production of Q_0 may also be plotted on a chart of the same type (see Fig. 2). The optimum combination of L and C should now be apparent. It is that combination where one of the expenditure lines is tangent to the physical curve (known as an "iso-product" curve). The total expenditure for this combination is given by:

$$E_0 = P_L L_0 + P_C C_0.$$

This expenditure is represented by the expenditure line pass-

ing through the point (L_o,C_o), since the same expression may be rewritten,

$$L_o = \frac{E_o}{P_L} - \frac{P_c}{P_L} C_o.$$

This procedure via calculus simply requires the equation of the slopes of the two lines, $-\frac{P_c}{P_L} = -\frac{\partial L}{\partial C}$,

where,

$-\frac{P_c}{P_L}$ = the slope of the expenditure lines, and

$-\frac{\partial L}{\partial C}$ = the slope of the iso-product curve.

Partial differential signs are used for the slope of the iso-product curve because it is in reality the horizontal cross section of a three-dimensional function relating Labor, Capital, and Output. Such functions are called "production functions."

If it is desired to determine the optimum combination of factors for other levels of output, the process is repeated with other iso-product curves. Those for higher outputs will lie to the right and above, those for lower outputs to the left and below. A curve comparing output and the expenditure which is least for each output is the "long-run" total cost curve for producing the product. This curve shows the cheapest way to produce any given output.

If there are more than two factors of production, say "A," "B," and "C," then the optimum combination is given by

$$\frac{P_A}{\partial A} = \frac{P_B}{\partial B} = \frac{P_c}{\partial C}.$$

safety factor, and operating pressure—for carrying a desired throughput? It should be noted that the length of line is irrelevant to this problem, since the cost per mile of trunk lines should not vary with length, be the lines 100 or 1,000 miles in length. Consequently, any costs which are proportional to length of line do not affect the choice of the optimum combination of the above variables. For example, it makes no difference to this problem whether a micro-wave or radio communication system is used; this is a decision that can be made on its own merits.

It is apparent that the solution of this problem with five variables is difficult. The use of the calculus with partial differentiation immediately suggests itself. A joint research group at the University of Oklahoma and Clark Bros., Inc. (a division of the Dresser industries) determined an "optimum" pressure and used a solution dependent on the calculus (this study covered gas pipe lines).[1] Mr. George C. Hughes determined an "optimum pressure," assumed a safety factor, and used an arithmetic determination of the optimum combination.[2]

This study will attempt to show that the problem can be reduced to two economic variables by the application of economic production function analysis and can then be solved either arithmetically or approximately by further application of the analysis.

According to economic production function theory, the minimum expenditure for producing a given output, Q_o, of some product which requires the combination of two "factors of production" (for example, Labor and Capital) may be determined readily if (1) the various physical combinations of the factors which will give the required output are known, and (2) the prices of the factors are known. The procedure is the following:

The total expenditure required for any combination of the two factors (designated "L" and "C") is given by:

$$E = P_L L + P_C C,$$

where,

E = the total expenditure,
L = the physical amount of labor used,
C = the physical amount of capital used,
P_L = the price of labor (per unit), and
P_C = the price of capital (per unit).

From this equation there may be deduced a family of expenditure lines,

$$L = \frac{E}{P_L} - \frac{P_C}{P_L} C.$$

There will be one such line for each possible expenditure (or each combination of L and C). These lines are parallel since all have the same slope, $-\frac{P_C}{P_L}$. If plotted on a chart where L is

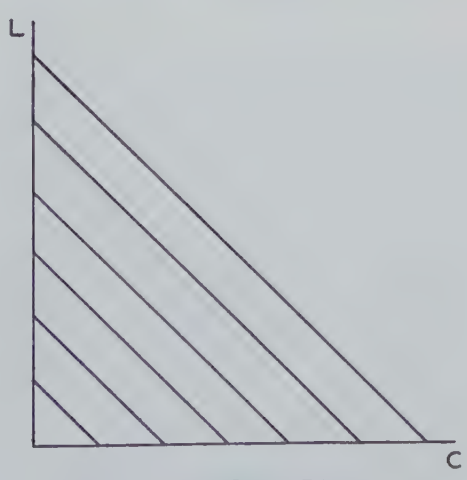


Fig. 1. Expenditure Lines.

This, in brief, is the process that will be used in the subsequent discussion of the physical variables.

A. *Safety Factor*

Although the safety factor question might validly be considered an economic one, it will be assumed here to be physical in nature. In a sense, it is an economic question to determine whether more money should be spent initially on capital investment in line pipe in order to reduce the probability of breakage, or whether more money should be spent for maintenance and repair in the future. However, it will be assumed that the purpose of the theoretical pipe lines designed here is to carry oil with a minimum probability of interruption of service in accordance with standard pipe strength characteristics. The safety factor used will, then, represent industry practice toward the difference which must be allowed between the bursting pressure for the steel in the line and the maximum pressure at which the line is to be operated. Unfortunately, there is some dispute as to just what the minimum allowable gap between bursting pressure (or minimum yield strength) and operating pressure should be.

Approximate safety factors (computed on a theoretical bursting pressure of 60,000 p.s.i.) on a number of recent large-diameter crude lines are shown in the sixth column of Appendix A. The range of these safety factors is 1.79 to 4.76. The approximate mean is 2.55. Consequently, it might be deduced that industry practice is about 2.5. However, it should be noted that lines have been built and are in operation with much smaller safety factors, *e.g.*, the Interprovincial and Standard of California lines (1.86 and 1.79 respectively). Furthermore, lower safety factors are being urged on the industry in technical articles and by govern-

ment agencies. For example, the Petroleum Administration for Defense uses 1.6 based on the minimum yield strength, the equivalent of about 1.8 on the bursting pressure.[4] This is about equal to the actual cases just cited. Consequently, in order to minimize costs, a safety factor of 1.8 will be used in this study. (It will be recognized that higher safety factors require thicker pipe for a given operating pressure; thicker pipe means more steel per mile of pipe line, and hence more expensive lines.)

B. *Optimum Pressure and Optimum Wall Thickness*

The safety factor problem can be assumed to be a physical one. The questions of the pressure and wall thickness to be used for a given line size are, however, another matter. While it is correct physically to say that for line pipe with an inside diameter of X it is necessary to apply a horsepower of Y in order to get a throughput of Z, it should be noted that the *cost* of throughput may also be a function of the pressure at which the line is operated and of the wall thickness used. It will be seen that wall thickness and pressure are in reality the same problem.

Physically, this pressure is more or less continuously variable below a maximum determined by the safety factor chosen in relation to the bursting pressure of a given size line. The minimum would have to be some pressure higher than zero; otherwise, the oil would have ceased to flow before reaching the station. Since the operating pressure may be varied within these limits, the size and number of stations may also be varied. If the costs of building and operating the pipe line were proportional to horsepower regardless of how the horsepower is applied, then operating pressure could be ignored as an economic variable. It would make no difference whether a few large or many small stations were used.

However, if costs vary with the way in which the horsepower is developed, *e.g.*, if it is more expensive to use small rather than large stations, pressure becomes a significant economic variable. The presence of operating pressure as a variable complicates the problem appreciably.

The question of optimum pressure has evidently plagued pipe line companies for many years, and industry practice still varies widely. Note the range of pressures used on the lines covered in Appendix A (650-1050 p.s.i.). As will be seen, a large range of pressures is not necessarily a criticism; indeed, it will be found that an even larger range than this should be used where the range covers all line sizes. However, there has been little agreement on the optimum pressure for any one line size. The question is often put in the form, what is the optimum pressure at which to operate a given size line? —where by size of line is meant standard *outside* diameters, *e.g.*, 20, 22, 24, etc., inches. The question posed in this form without further elaboration is illogical.

There is a family of lines with varying inside diameters for each standard outside diameter. It is these *inside* diameters, not outside diameters, which are critical in the determination of the horsepower required to move a given throughput. Pressure must be applied to the oil to overcome friction generated when the oil touches the pipe. Obviously it is the inside area, not the outside area, of the pipe that determines the amount of friction generated. Consequently, for any given outside diameter size, there will be at least as many different total horsepower requirements (and hence pressure requirements) for a given throughput as there are inside diameters available. Indeed, physically there will be a very large number of possible pressures for each inside diameter size available—the almost infinite number which may be developed between the limits set out above (a low suction

pressure and the safety-factor maximum). It is therefore illogical, without further elaboration, to attempt to determine which pressure is the optimum for any outside-diameter line; rather this question must be answered for each inside-diameter line.

The conclusion that follows from this argument is that it would be most desirable to eliminate the question of operating pressure as a variable. Physically it is a variable; in an economic sense, however, it may well not be. In the first place, if there are any decreasing costs per horsepower present in the operation of pumping stations, then the (economic) optimum pressure is fixed at the maximum pressure for any pipe of a given inside diameter at which the line can be operated in accordance with the safety factor and the yield strength. The existence of decreasing costs per horsepower in the operation of stations would mean that a given horsepower could be produced at the lowest total cost by the use of the smallest possible number of stations, where the minimum limit on the number of stations is determined by their maximum possible operating pressures. Since there clearly *are* decreasing costs in operating stations of a given type (for example, a labor force of two operators on each shift is necessary for semi-automatic stations having small horsepower capacities, but the same number of workers can operate stations with capacities upwards of 5,000 horsepower), the optimum pressure at which any line of a given *inside* diameter may be operated is the maximum. Consequently, on economic grounds, it is possible to eliminate many of the physical possibilities. Any pipe line of a given inside diameter must be operated at the maximum pressure possible in accord with the safety factor; otherwise, more stations will be built than are necessary, and more money will be spent than is necessary—both in initial station outlay

and subsequent wage, maintenance, and power bills. It is for this reason that wall thickness and operating pressure may be considered one problem. There is only one economically acceptable pressure for any given inside-diameter pipe, *viz.*, the maximum possible in accord with the safety factor chosen.

This reduces the problem to one pressure per inside-diameter line, but there are over 100 such lines available in the usual outside-diameter range of crude oil lines (8-32 inches). The concept of an optimum pressure for a given outside-diameter line, which was uncharitably described above, remains to be considered. This concept is valid if, and only if, one size of pipe (or combination of sizes) within a given *outside*-diameter family can carry all possible throughputs at a lower total cost than any other line (or combination) in that family. In this case the optimum pressure for the outside diameter under consideration would be the optimum for the particular inside-diameter pipe which carries any throughput cheaper than does any other inside-diameter pipe in the family. This optimum pressure would be the maximum at which the optimum inside-diameter pipe (or combination) could be operated. For any one throughput, the condition is not so stringent—there need only be one inside diameter or combination that is most economical.

Is it possible that one inside-diameter size within an outside-diameter family can satisfy the conditions of such an economic optimum? In any given outside-diameter family, the lowest investment cost for line pipe is obtained by using the minimum wall thickness which can be handled in laying without excessive bending and buckling; this is usually considered to be ¼-inch wall pipe. The thinnest wall has the lowest line pipe investment cost simply because it has less steel per foot. For example, ¼-inch, 20-inch pipe weighs 139

tons per mile, while ½-inch, 20-inch pipe (the thickest wall available in standard line pipe) weighs 275 tons per mile. (Lest the reader think that this discussion of optimum pressures is academic, he is invited to consider pipe costs for a thousand mile line using first ½-inch pipe and then ¼-inch-pipe—the difference for 20-inch pipe at $166 a ton is about 22.5 million dollars.)

Not only does the pipe with the thinnest wall have the least line pipe investment cost, it would also require the lowest total horsepower for a given throughput of any inside-diameter line (or combination of lines) within a given outside-diameter family. The reason for this is that the pipe with the minimum wall thickness has the largest inside diameter. It requires more horsepower to push a given amount of oil through a small (inside diameter) pipe than through a large (inside diameter) pipe. Remember that it is the inside surface area which matters in arresting liquid flow *via* friction. There is less friction per barrel of oil carried in, say, a 29.5-inch (inside diameter) pipe than in a 29.0-inch (inside diameter) pipe because there is less surface area per barrel of oil. An open-end cylinder of inside radius "r" and length "L" has a volume of $\pi r^2 L$ and an inside surface area of $2\pi rL$. An open-end cylinder of inside radius "$r + .5$" and length "L" has a volume of $\pi(r + .5)^2 L$ and has an inside surface area of $2\pi(r + .5)L$. The volume increases more than the surface area; consequently, in the larger pipe more oil touches less surface per barrel. This means that less friction per barrel is created and that less horsepower per barrel is needed. Consequently the ¼-inch pipe not only has the lowest steel investment cost, it also has the least total horsepower requirements and hence the least total horsepower investment (and operating) costs. The magnitude of the latter saving is not appreciable in relation to that of the former, but the important point is that no

other inside-diameter pipe has a *smaller* horsepower requirement for any given throughput.

Now if the ¼-inch pipe has the lowest line investment cost and the lowest total horsepower requirements of any line in a given outside-diameter family, the immediate presumption would be that it would have the lowest cost in the outside-diameter family of carrying any throughput. However, the pipe with the minimum wall thickness will also have the lowest bursting pressure; consequently the maximum pressure at which it can be operated will be the least (maximum) of any line in the family. This means that less advantage can be taken of decreasing costs in the construction and operation of stations on this line than on any other line in the family. If the gains from decreasing station operating costs obtained by utilizing thicker pipe of the same outside diameter should offset (1) the increased line pipe costs and (2) the increased horsepower required, then the minimum wall thickness would *not* be the optimum size. Such a situation seems on an *a priori* basis to be unlikely. The remainder of this section will be devoted to an investigation of this question by the use of applied economic production function theory.

What other programs than ¼-inch pipe might be used? Many have been used (see Appendix A); indeed, only one line in the tabulation in Appendix A uses ¼-inch pipe throughout. For large-diameter pipes, standard API wall thicknesses include ½, 7/16, ⅜, 5/16, 9/32, and ¼ inches. Technologically, any of these could be used instead of ¼-inch throughout. Would any of them give a lower total cost?

Some of the alternatives which are technologically feasible can be eliminated by economic logic. It would be irrational, from a cost point of view, to lay a line with any one thickness

of pipe throughout except (perhaps) ¼-inch. The reason for this is that pressure falls as oil moves downstream from a pumping station. Consequently, the line may be "telescoped." That is, when the pressure has fallen sufficiently that the next smaller thickness may be substituted without exceeding the line safety factor, pipe of the same outside diameter with the next thinner wall may be used. Economically this substitution *should* be carried out, everything else being equal, since the thinner wall pipe uses less steel per mile and also requires somewhat less horsepower to move a given throughput. Using the initial pipe, say ½-inch, beyond the point where 7/16-inch could be used incurs an unnecessary cost and must therefore be rejected. This proposition may be extended in steps to the thinnest usable pipe, *viz.*, ¼-inch throughout.

In short, the use of any single line thickness, other than ¼-inch, throughout the length of the line is economically irrational. Therefore, the only economic alternatives to ¼-inch pipe throughout are completely telescoped lines beginning with each of the available wall thicknesses. This proposition should probably be modified to this extent: there are at least two disadvantages of telescoping. One is that line capacity cannot be expanded with stations of the original size without digging up and relaying sections of the line. Another is that there must be considerable problems of logistics involved in getting the right wall thickness at the right place at the right time when the line is being laid. Either or both of these difficulties might tempt a company to avoid complete telescoping and to use, say, two sizes of pipe, perhaps 7/16-inch and ⅜-inch. However, the very large initial cost differences relative to complete telescoping would seem to make such a decision indefensible in the end. Such a decision on a 26-inch, 1,000-mile line would mean a loss of about 15 million dollars on steel costs (at $166 per ton

delivered). On the other hand, where the decision lies between, say, 5/16, 9/32, and 1/4 versus 5/16 and 9/32, there would be more of a case for dropping the 1/4-inch pipe because the cost savings are not so appreciable (there might be even *more* of a case for dropping the 5/16 and 9/32). If the decision lies between 9/32 and 1/4 versus 1/4, there would be a considerable argument for dropping the 9/32, should the cost differences be slight.

At what station operating pressure should each of these possible piping programs be operated? At the maximum pressure permissible in accord with the safety factor for the initial (thickest) segment of the line. Otherwise, as was shown above, there will be more stations built than necessary, with resultant unnecessary expenditures.

The number of alternative piping programs which might be economically acceptable has now been reduced to seven, each of which is operated at the highest operating pressure possible in accord with the safety factor chosen and the wall thickness of the thickest segment of the line. It is now in order to compare the costs of these lines with those of lines 1/4-inch throughout.

To review, what happens when telescoped lines are substituted for 1/4-inch pipe throughout? As was indicated above, three things happen: (1) the amount of steel used rises, since the 1/4-inch pipe has the minimum possible amount of steel; (2) the total horsepower required for a given throughput rises slightly since the volume of lines within an outside-diameter family falls slightly as the wall thickness of the pipe increases; (3) the number of stations required falls, since the thicker wall pipe, which is stronger, can be operated at higher pressures than can the 1/4-inch pipe, which is the weakest as well as the lightest in any outside diameter

family. The first two changes are in the direction of lower costs; the last tends to offset these savings. Does it offset the saving sufficiently to lead to a net increase in costs?

A physical relationship can be deduced between the various piping programs and the number of stations; furthermore this relationship can be priced. Consequently, it is possible to determine the optimum combination, so to speak, of stations and wall thicknesses for any given throughput. Once this is done, any cost savings resulting from lines other than ¼-inch throughout may be compared with the insignificant increases in costs arising from increased total horsepower.

The only changes in line costs associated with changes in inside diameters within an outside-diameter family are the cost of line pipe plus the cost of freight for transporting it. All other line costs variant with diameter (*e.g.*, pipe coating) vary with *outside*, not inside, diameter and are hence the same for all inside-diameter lines in a given outside-diameter family. As a result, all changes in line costs which would occur from substituting telescoping can be related to the changes in steel tonnages required. Both pipe and freight costs are a function of tonnage: pipe costs used in this study are $145 per ton (1952 prices), while approximate average freight costs are $21 per ton, giving a total cost of $166 per ton of steel added. This initial outlay amounts to $19.3667 per ton per year, assuming a 15-year life, four per cent interest rate, and one per cent property tax rate.

The relevant station cost changes can be related to the number of stations. What is it that makes it necessary to use the smallest possible number of stations for any given inside-diameter line? The costs which are *common* to all stations of

a particular type and which, therefore, vary with the number of stations used, not with the total horsepower produced. It is only changes in these costs which would yield appreciable savings from decreasing the number of stations; costs which vary principally with horsepower requirements (*e.g.*, motors, switchgear, etc.) remain almost the same regardless of the number of stations used to produce a given horsepower. The costs common to all semi-automatic stations pumping, as an example, 250,000 barrels per day are summarized below (again assuming a 15-year life):

SUMMARY OF COMMON STATION COSTS
(250,000 B/D; 1952 dollars)

Initial Outlay	
Initial material costs excluding pumps	$143,935
Pumps	49,500
Initial service costs	211,900
Total initial costs	$405,335
Annual Costs	
Initial outlay at 11⅔%*	$ 47,290
Operating labor	47,000
Maintenance	8,600
Total per station	$102,890

* 15-year life, 1% per annum property tax, 4% per annum opportunity cost (interest).

The total common cost per station per year is $102,890. Each station saved by moving from ¼-inch pipe throughout to telescoped pipe will, then, mean an annual saving of $102,890. On the other hand, each ton of steel added will mean an increased steel cost of $19.3667 per year. If adding a station saves $\frac{102{,}890}{19.3667} = 5313$ tons of steel (or more), it is economical to add it; otherwise it is not.

The required tonnage of steel and number of stations for each of the seven potentially acceptable piping programs for a 30-inch line carrying 250,000 B/D are shown in Table 1 and Chart 1. (The 30-inch line is indicated to be the optimum outside diameter in Section V.) The process of computation first involved determining the pressure drop per mile (60 SUS, 34° gravity crude) in each size pipe. Then, beginning with the optimum pressure for ½-inch (the maximum permissible in accord with the safety factor), a computation was made of the number of miles necessary for the pressure to drop to a level which could be accommodated by the next smaller wall thickness. This was continued until ¼-inch pipe was reached; the mileage of ¼-inch pipe was determined by ascertaining how many miles are necessary before the pressure falls to the station suction pressure (assumed to be 20 p.s.i.). The total mileage of all sizes then gives the total pipe mileage between stations. The number of stations is determined by dividing the total pipe mileage (here assumed to be 1050) by the mileage between stations.

TABLE 1

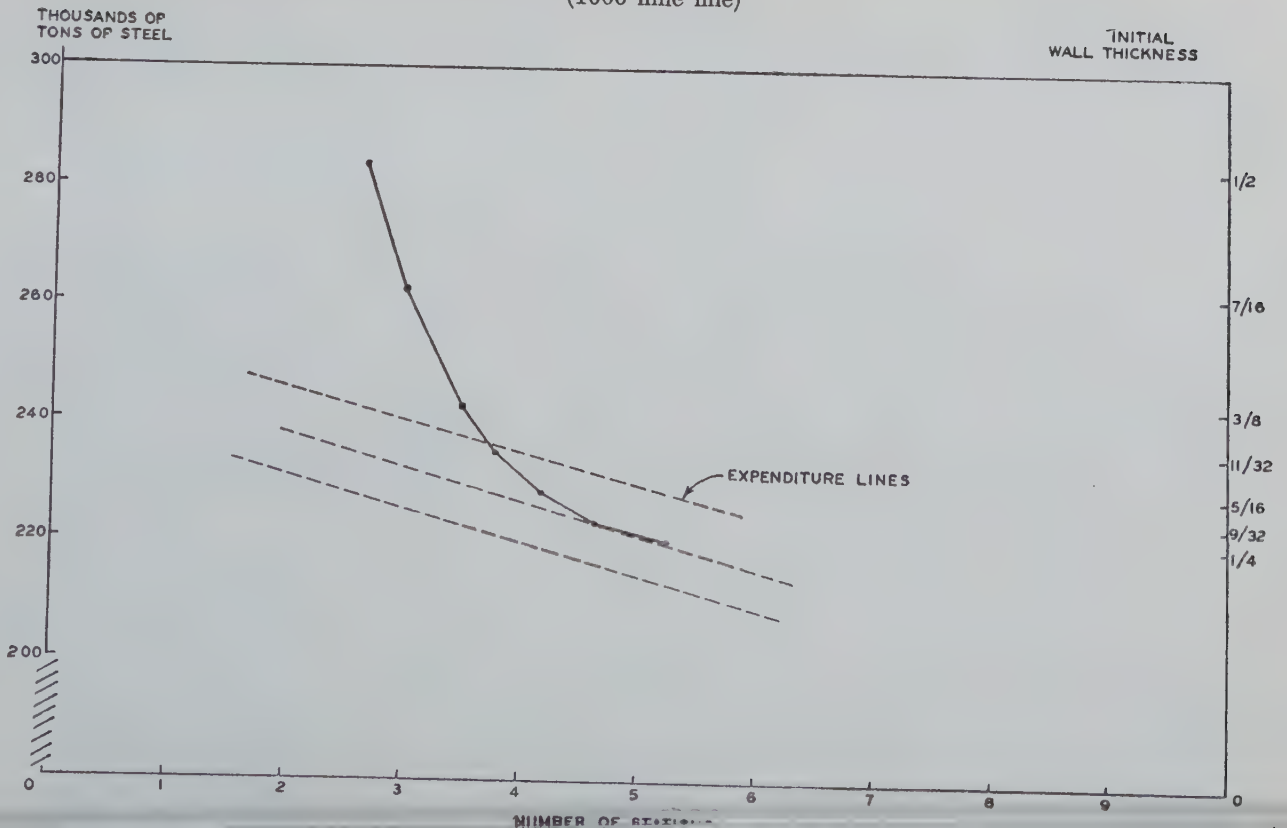
OPTIMUM PIPING PROGRAM COMPUTATION—30-INCH, 1000 MILE LINE; 250,000 BARRELS PER DAY

Piping Program	Tons of Steel	No. of Stations	Annual Costs		
			Steel	Common Station	Total
	(000)		$000		
Telescoped—½ in. initial	283.5	2.623	5,489.5	269.9	5,759.4
Telescoped—$\frac{7}{16}$ in. initial	262.5	2.982	5,083.4	306.8	5,390.2
Telescoped—⅜ in. initial	242.9	3.466	4,704.5	356.6	5,061.1
Telescoped—$\frac{11}{32}$ in. initial	235.2	3.777	4,555.1	388.6	4,943.7
Telescoped—$\frac{5}{16}$ in. initial	228.5	4.160	4,424.4	428.0	4,852.4
Telescoped—$\frac{9}{32}$ in. initial	223.3	4.626	4,324.4	476.0	4,800.4
¼ inch throughout	220.2	5.217	4,264.3	536.8	4,801.1

Source: See text, pages 49–50.

CHART 1

Tons of Steel and Number of Stations—30-inch Line Carrying 250,000 Barrels Per Day.
(1000 mile line)



The optimum combination of stations and steel is determined by finding the point on the curve in Chart 1 which is tangent to an expenditure line derived from the annual costs shown above.

$$E = P_T T + P_S S,$$

where,

E = a given expenditure,
T = tonnage of steel,
S = number of stations,
P_T = delivered price of steel (per ton), and
P_S = common price of stations (per station).

Or, substituting the annual prices,

$$E = 19.3667T + 102{,}890S.$$

This may be solved for T as follows:

$$T = \frac{E}{19.3667} - \frac{102{,}890}{19.3667} S.$$

$$= \frac{E}{19.3667} - 5313S.$$

Several of these expenditure lines are drawn around the curve in Chart 1. The choice is more or less indifferent between one-stage telescoping (9/32 and 1/4-inch pipe) and 1/4-inch pipe throughout, but the former is slightly cheaper (see Table 1). The saving from one-stage telescoping is so small as to be of questionable significance; in any event, the small saving would be offset by increased horsepower requirements. Therefore, it may be concluded that 1/4-inch pipe is the most economical piping program for this line size and throughput with the prices used. Once this is established, then operating pressure is also removed from the

problem as a variable, since the optimum pressure for any line has been shown to be the maximum possible. The maximum for ¼-inch, 30-inch pipe is its optimum and is also the optimum for *all* 30-inch pipes, since ¼-inch pipe carries this throughput at less expense than does any other 30-inch piping program.

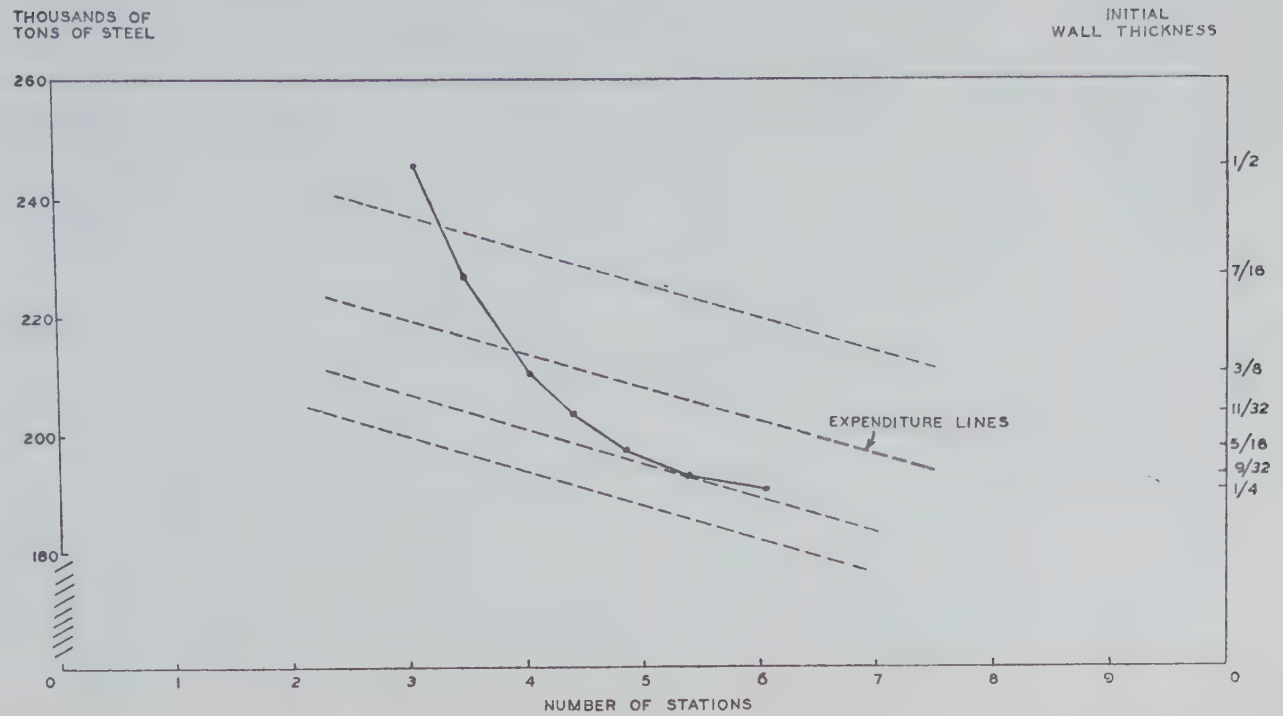
In summary, wall thickness and operating pressure have been removed as variables, for this particular example, leaving only two variables remaining: (1) outside line diameter, and (2) horsepower. This makes the optimum combination solution appreciably less difficult.

Before proceeding to the pricing of these two factors of production, it is necessary to investigate the piping problem for other examples—lest the reader be disturbed by generalizations based on a single example.

The optimum outside diameter line size for 200,000 barrels per day is (see Section V) 26 inches. The same expenditure line may be applied to a physical relationship between stations and steel (see Chart 2). Here one-stage telescoping is the most economical. When this is the case, it is necessary to consider the effect of the small increase in total horsepower requirements. Such a computation was made, but the small increase in horsepower cost was insufficient to change the optimum piping program. The net saving relative to ¼-inch pipe throughout is about $17,000 per year. Since this is only about 0.4 per cent of total annual common station costs and steel costs, the difference may not be significant. Similar computations were carried out for 300,000, 350,000, and 400,000 barrels per day using 32-inch pipe. These computations showed that either ¼-inch throughout or one-stage telescoping were the optimum combinations. The maximum difference was some 80 thousand dollars per year,

CHART 2

Tons of Steel and Number of Stations—26-inch Line Carrying 200,000 Barrels Per Day.
(1000 mile line)



about 0.5 per cent of the total involved. In these cases the economically optimum pressure is again determinant for the throughput in question. It is a managerial question whether ¼-inch pipe throughout or one-stage telescoping should be used when the small cost differences and the problems created by telescoping are considered.

While this discussion may read like a brief for ¼-inch pipe throughout, it should be emphasized that the most economic of the seven alternative systems depends on the relative prices of steel and stations. Should the line be laid in an area close to a pipe mill, freight costs and hence the delivered price of pipe would fall. It would, therefore, be economical to substitute steel for stations, *i.e.*, to use telescoping. On the other hand, should the recent rise in steel prices be higher proportionately than any increases in common station costs that may have occurred since the end of price controls, stations should be substituted for steel, thereby strengthening the case for ¼-inch pipe. Price changes would, however, have to be appreciable before it would be possible to invalidate the proposition that the most economical piping programs are basically ¼-inch. A 30-inch line using one-stage telescoping is 89 per cent ¼-inch pipe; even completely telescoped lines, beginning with ½-inch pipe, are 50 per cent ¼-inch throughout. As was pointed out above, non-telescoped piping programs, other than ¼-inch, must be rejected, subject to the disadvantages of telescoping, since wall-thicknesses greater than necessary for the line pressures would be used.

Even should the answer be changed by the use of different prices, changing the answer does not invalidate the process used. By the application of the proper prices (delivered steel costs and common station costs) to the physical

relationship existing between steel tonnage and number of stations, it is possible in any given case to eliminate operating pressure and wall-thickness as variables, regardless of whether ¼-inch throughout, one-stage, or six-stage telescoping is used.

C. *Line Diameter and Horsepower*

Now that a method has been established for the removal of pressure and wall thickness as variables, it is possible to turn to the most important problem—the determination of the optimum combination of *outside* line diameter and horsepower for any given throughput. This problem can be described more simply as the determination of the optimum line size for carrying any given throughput. Once a throughput and line size are stipulated with safety factor, wall thickness, and pressure pre-determined, then horsepower is determinant.

A physical relationship between horsepower, line diameter and throughput may be worked out by the use of a suitable hydraulic formula. Such a relationship is shown in Table 2 and Chart 3 for a 1000 mile pipe line having no net gravity flow and a five per cent terrain variation. These data encompass throughputs of 25, 50, 75, 100, 125, 150, 200, 250, 300, 350, and 400 thousand barrels per day. A number of line sizes (outside diameter) have been chosen for each throughput; the complete range of line sizes is 8⅝-inch through 32-inch. The thickness of each line has been assumed to be ¼-inch throughout. While this may depart slightly from minimum costs where one- or two-stage telescoping is the optimum instead of ¼-inch, the departures are insignificant in relation to total cost. For example, a test computation for a 30-inch line showed that the maximum saving from the use

TABLE 2

COMPUTATION OF HORSEPOWER REQUIRED TO MOVE VARIOUS THROUGHPUTS THROUGH VARIOUS SIZES OF LINES—USING ¼-INCH WALL, GRADE "B," A.P.I. STANDARD X-42 PIPE
(60 SUS, 34° Oil; Safety Factor of 1.8)

Throughput Barrels per Day	Outside Diameter Inches	"Optimum" Discharge Pressure (psi)	Total Hydraulic Horsepower	Station Horsepower (20 psi Suction Pressure)	Number of Stations
25,000	8⅝	1933	9,806	813	12.06
	10¾	1550	3,264	650	5.02
	12¾	1306	1,403	546	2.57
50,000	8⅝	1933	65,283	2165	30.15
	10¾	1550	21,729	1300	16.71
	12¾	1306	9,342	1093	8.55
	14	1189	5,897	994	5.93
	16	1044	3,066	871	3.52
	18	929	1,726	774	2.23
75,000	8⅝	1933	197,885	2439	81.13
	10¾	1550	65,864	1951	33.76
	12¾	1306	28,319	1640	17.27
	14	1189	17,878	1491	11.99
	16	1044	9,293	1305	7.12
	18	929	5,231	1160	4.51
	20	833	3,134	1038	3.02
	22	758	1,974	940	2.10
100,000	10¾	1550	144,663	2601	55.62
	12¾	1306	62,198	2186	28.45
	14	1189	39,265	1987	19.76
	16	1044	20,414	1740	11.73
	18	929	11,490	1544	7.44
	20	833	6,883	1382	4.98
	22	758	4,335	1253	3.46
	24	694	2,844	1147	2.48
	26	642	1,933	1056	1.83
125,000	12¾	1306	114,506	2734	41.88
	14	1189	72,286	2484	29.10
	16	1044	37,581	2176	17.27
	18	929	21,154	1932	10.95
	20	833	12,674	1727	7.34
	22	758	7,982	1568	5.09
	24	694	5,238	1431	3.66
	26	642	3,557	1322	2.69
	30	556	1,785	1137	1.57

TABLE 2—(*continued*)

Through-put Barrels per Day	Outside Diameter Inches	"Optimum" Discharge Pressure (psi)	Total Hydraulic Horse-power	Station Horse power (20 psi Suction Pressure)	Number of Stations
150,000	14	1189	119,021	2981	39.93
	16	1044	62,019	2611	23.75
	18	929	34,910	2318	15.06
	20	833	20,915	2073	10.09
	22	758	13,171	1882	7.00
	24	694	8,645	1719	5.03
	26	642	5,873	1587	3.70
	30	556	2,945	1370	2.15
	32	521	2,160	1278	1.69
175,000	16	1044	94,322	3047	30.96
	18	929	53,095	2705	19.63
	20	833	31,809	2419	13.15
	22	758	20,034	2197	9.12
	24	694	13,147	2004	6.56
	26	642	8,931	1849	4.83
	30	556	4,480	1594	2.81
	32	521	3,284	1493	2.20
200,000	16	1044	135,901	3482	39.03
	18	929	76,497	3091	24.75
	20	833	45,829	2764	16.58
	22	758	28,863	2510	11.50
	24	694	18,941	2290	8.27
	26	642	12,866	2116	6.08
	30	556	6,453	1823	3.54
	32	521	4,736	1704	2.78
250,000	18	929	140,832	3864	36.45
	20	833	84,371	3455	24.42
	22	758	53,134	3137	16.94
	24	694	34,871	2865	12.17
	26	642	23,690	2644	8.96
	30	556	11,883	2276	5.22
	32	521	8,708	2129	4.09
300,000	20	833	138,914	4147	33.50
	22	758	87,485	3764	23.24
	24	694	57,416	3438	16.70
	26	642	39,000	3173	12.29
	30	556	19,564	2732	7.16
	32	521	14,341	2556	5.61

TABLE 2—(*continued*)

Throughput Barrels per Day	Outside Diameter Inches	"Optimum" Discharge Pressure (psi)	Total Hydraulic Horsepower	Station Horsepower (20 psi Suction Pressure)	Number of Stations
350,000	22	758	133,363	4391	30.37
	24	694	87,519	4011	21.82
	26	642	59,452	3702	16.06
	30	556	29,821	3189	9.35
	32	521	21,860	2982	7.33
400,000	24	694	126,106	4584	27.51
	26	642	85,660	4230	20.25
	30	556	42,969	3645	11.79
	32	521	31,498	3405	9.25

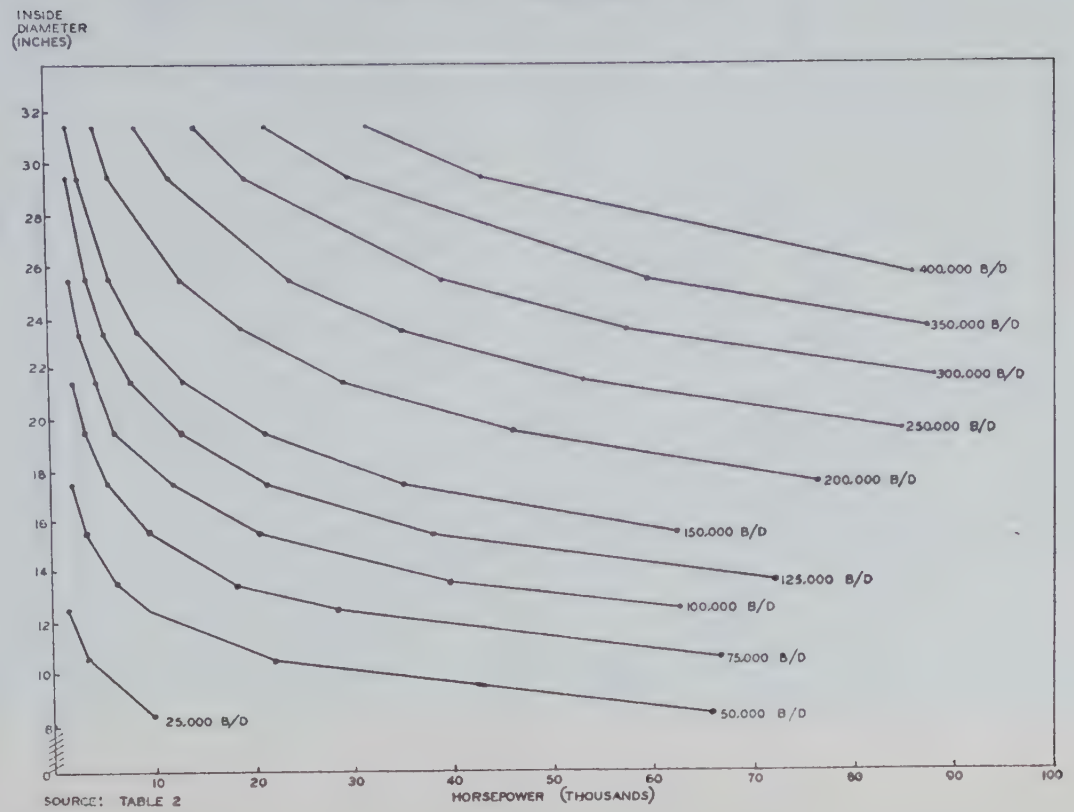
Note: $HP = \frac{T^{2.735}}{(D^{4.735})\ (C)}$

Where, HP = Total Horsepower
T = Throughput
D = Inside Diameter
C = Constant
Source: Computed using A.P.I. specifications for line pipe.

of one- or two-stage telescoping on all throughputs from 150-400,000 barrels per day amounted to only 0.56 per cent of total cost. The statistical advantages arising from uniform treatment of the cost problem by the use of ¼-inch pipe were felt far to outweigh any such gain in accuracy as one-half of one per cent; furthermore, such a gain might well not be statistically significant. Each line is operated at the maximum pressure permissible for ¼-inch pipe in accord with a safety factor of 1.8 relative to the bursting pressure, assuming an average tensile strength of 60,000 p.s.i.

Chart 3 is analogous to a traditional physical production function relating two factors of production (in this case line diameter and horsepower) with output (throughput). This, as was shown above, is half the information required for determining the optimum, *i.e.*, cheapest, combination of the

Production Function for Crude Oil Pipe Lines, Line Diameter Versus Horsepower Versus Throughput.
(1000 mile lines)



two factors. The other half of the required information is the price of the factors. It is to the determination of these prices that the next three sections of the study will be devoted. It should be noted that these are what might be termed "composite" factors of production in that each encompasses many items. For example, the price of line diameter includes all initial outlays variant with line diameter, *e.g.*, the cost of pipe, pipe coating, anodes, etc. The price of horsepower includes all initial outlays for stations (pumps, motors, switchgear, buildings, etc.) and all subsequent expenditures (power, labor, and maintenance) for pumping. There are other costs invariant with either line diameter or horsepower. These do not affect the optimum combination problem, but they cannot be ignored in a complete tabulation of costs. Consequently, they will be determined apart from the more important items in Section IV and added into the cost curves in Section V.

II. Costs Variant with Diameter of Line

All significant costs variant with diameter are included in the initial outlay for the pipe line. Subsequent expenditures on the line proper do not vary sufficiently with diameter to be of interest here. Some of the cost items lend themselves to engineering computation. Others do not. Where engineering estimation is feasible, it was used; otherwise actual historical cost data were used as the basis for the average costs computed for the study. It has been assumed that the pipe lines to be designed in this study are trunk lines 1000 miles in length; however, the costs should be applicable to all but the very short lines, say, less than 75 or 100 miles. The costs per mile of a 1000 mile line should be the same as those of a similar 200 mile line.

The pipe lines have been assumed to be "level." More precisely, it has been assumed that there is no net gravity flow of oil. In other words, should the end of the line be at a lower altitude than the beginning, in order for the costs to apply there would have to be sufficient uphill terrain along the way to offset this natural gravity pull downward. Or the line may have terminals at the same altitudes, but be laid across hills; the costs will still apply as long as uphill mileage is offset by downhill mileage. (The level line assumption affects only the station costs, not the line costs.) An average amount of such uphill and downhill terrain might add five per cent to the length of the line. Consequently, it has been assumed that there is a five per cent terrain variation on each of the lines. This means that there will be 1050 miles of pipe between terminals which are 1000 overland miles apart.

Certain other terrain assumptions were also necessary. First, as an approximation based on actual cases, five miles of "casing crossings" were included (crossing beneath highways, railroads, etc.). In addition, it was assumed that the lines would have six miles of river crossings, half over major rivers requiring dual lines for emergency use in case of breakage. Finally, it was assumed that there would be on the average 100 miles of unusually difficult, rock trench digging.

All costs in the study are based on prices appropriate in mid-1952.

The most important items of line costs which vary with diameter are line pipe and the freight thereon, material for corrosion protection, line valves and fittings, structural and reinforcing steel, and the construction services needed to lay the line. These initial costs are summarized in Table 3. While

a complete description of the process of computation of the costs of the various items is not feasible here, the general procedures for the important items will be discussed in the remainder of this section.

Line Pipe—The computation of line pipe costs involved a direct physical determination of the average amount of steel required for the various lines covered in the study, followed by the pricing of these tonnages with 1952 line pipe prices ($145 per ton). In order to make these computations, it is necessary simply (1) to compute the volume of a given length of pipe, in accord with the principles of solid geometry, of the required outside diameter and wall thickness (¼-inch) and (2) to multiply by an average density of line pipe steel (0.2833 pounds per cubic foot). The tonnage of steel in, say, a mile of pipe can then be multiplied by $145 to get the cost per mile of line pipe and by 1050 to get the cost per 1000 mile line having a five per cent terrain variation. This computation carried out for each line under consideration gives the cost of the most important capital item.

Additional pipe is necessary for the casing crossings and river crossings. (Casing crossing steel consists of an extra length of pipe of a larger outside diameter than the main line which is used to enclose the line proper where it passes under the highway or railroad.) Casing crossings need only thin-wall pipe. The cost of this for each line is the cost of five miles of ¼-inch pipe of the next larger outside diameter.

River crossings require thick-wall pipe in order to minimize the danger of breaks; furthermore, on wide river crossings dual lines are used in order to insure service in case of breakage. Extra river-crossing steel costs were computed from the quantities of steel necessary for (1) three additional miles of ½-inch pipe for the dual lines and (2) an additional ¼-inch of steel on all crossings.

TABLE 3

LINE COSTS VARIANT WITH DIAMETER OF LINE—¼-INCH PIPE THROUGHOUT; 1000 MILE LINE
(1952 Dollars)

Line Size (O.D.)	Main Line Pipe	Other Line Pipe[1]	Freight on Pipe	Total Pipe and Freight	Primer	Enamel	Fiberglass	Asbestos Felt Wrapping	Magnesium Anodes	Backfill Lead Wires etc.	Total Corrosion	Construction Service[2]	Engineering and Supervision	Valves and Fittings	Structural Steel	Misc.	Minor Costs[3]	Grand Total
	Thousands of 1952 Dollars																	
8¼	8,987.3	151.8	1,323.6	10,462.7	22.7	204.1	177.5	213.5	30.7	6.4	654.9	7,140	1,000	70	105	200	11.6	19,644.2
10¾	11,270.5	188.1	1,659.5	13,118.1	28.4	253.8	220.3	265.0	38.3	8.0	813.8	8,610	1,100	76	120	200	14.5	24,052.4
12¾	13,416.7	219.0	1,974.8	15,610.5	33.1	300.6	260.6	313.5	45.4	9.5	962.7	10,300	1,400	86	135	200	17.6	28,711.8
14	14,755.2	244.5	2,172.4	17,172.1	36.9	329.9	285.8	343.8	52.5	11.0	1,059.9	11,150	1,500	95	150	220	20.8	31,367.8
16	16,901.5	279.3	2,488.3	19,669.1	41.6	376.7	326.1	392.3	57.0	12.0	1,205.7	13,750	1,800	103	165	220	24.2	36,937.0
18	19,048.0	314.9	2,804.3	22,167.2	47.3	423.5	366.4	440.7	64.1	13.4	1,355.4	17,450	2,100	113	180	220	30.3	43,615.9
20	21,194.3	348.8	3,120.0	24,663.1	52.0	470.3	406.6	489.2	71.3	15.0	1,504.4	20,750	2,400	143	195	220	38.9	49,914.4
22	23,342.1	383.5	3,436.1	27,161.7	57.6	517.1	446.9	537.7	78.4	16.4	1,654.1	22,250	2,700	146	195	240	44.3	54,391.1
24	25,488.3	418.3	3,752.0	29,658.6	62.4	563.9	487.2	586.1	85.5	17.9	1,803.0	23,600	3,000	181	210	240	48.5	58,741.1
26	27,634.7	453.3	4,069.4	32,157.4	68.0	610.7	527.5	634.6	92.6	19.4	1,952.8	25,700	3,300	197	210	240	63.0	63,830.2
30	31,927.6	522.5	4,699.7	37,149.8	80.3	704.3	608.1	731.5	110.7	22.4	2,257.3	28,500	3,800	251	225	240	76.1	72,499.2
32	34,074.0	557.4	5,015.6	39,647.0	85.1	751.1	648.4	780.0	114.0	23.9	2,402.5	31,300	4,100	316	225	240	89.0	78,319.5

Source: See Section II (next to last column from Section IV)
Notes: 1. River and casing crossings
2. Includes labor and some construction materials
3. See Section IV
Assumptions: 1000 mile line; no net gravity flow; 5 per cent terrain variation; 10 per cent rock trench digging; 5 miles casing crossings; 6 miles river crossings, all dual-line.

Pipe freight costs, the only freight costs sufficiently important to be distinguished, are a function of the weight of pipe used and of the distance of the line from the pipe mills. The latter will, of course, depend on where the line is laid. Consequently, any general study can only approximate such costs. As an approximation, the freight rate from Pittsburgh to the Gulf Coast ($21 per ton) was used. Freight costs are determined by multiplying steel tonnages by this freight rate.

Corrosion Protection—Pipe coating is used to protect the pipe from the corrosive action of the soil in which it is laid. The coating costs used here follow the best practice which requires, first, the application of a primer (a thinned solution of coat-tar pitch) to the cleaned surface of the pipe in a coat of negligible thickness. Second, a coat of hot coal-tar enamel is applied to a thickness of, on the average, some $\frac{3}{32}$ inches. Third, a fiber glass paper fabric is laid on the enamel while the enamel is still molten, with a spiral wrapping and a lapover of about $\frac{3}{4}$ inch on the average. Finally, the cooled enamel, already impregnated with the fiber glass paper, is coated with a spiral wrapping of asbestos felt paper, again with a lapover of about $\frac{3}{4}$ inch. In order to compute the costs of pipe coating, the physical quantities of each layer necessary to cover 1050 miles of each size of pipe were first determined. This computation involved, basically, the determination of the surface area to be covered, together with thickness allowances where necessary. The physical quantities necessary were multiplied by prices from a leading manufacturer to get dollar costs.

Magnesium anodes are eventually installed on most pipe lines as a further means of protection from the corrosive effects of the soil. If a line were completely coated in accord

with the best coating practices, there would be no need for anodes. However, parts of the line cannot be coated, *e.g.*, the line valves. For this reason anodes are used eventually on most lines. It should be apparent that anode requirements will vary widely from pipe line to pipe line (indeed along the same line) with variations in the type of soil through which the line is laid and with variations in the amount of surface coated. In order to compute anode costs it was necessary to choose averages based on actual experience. A leading consulting corrosion engineer estimates that on the average a line coated in accordance with the best practices will have not more than two per cent bare surface; an average current required to protect the line is two milliamperes per square foot of exposed metal surface. Cathodic protection is usually designed to last ten years. Each pound of magnesium can generate 500 ampere-hours of current before being completely sacrificed. The amount of magnesium required can then be computed from the following relationship:

$$\text{Weight of magnesium required} = \frac{(.02)\ (\text{area of 1050 miles of pipe})\ (.002\ \text{amps})\ (\text{no. of hours in 10 years})}{500\ \text{ampere-hours per pound of magnesium}}$$

$$= 0.0070128\ (\text{area of 1050 miles of pipe}).$$

This required weight of magnesium was converted to dollars by multiplying by an appropriate price per pound furnished by a leading manufacturer of anodes. This price varies with the size of the anode; that chosen was the price per pound of the most common size, *viz.*, seventeen pounds. The number of anodes must also be computed in order to determine backfill and connecting-wire costs. This is done by dividing total magnesium requirements by seventeen and multiplying by appropriate backfill prices.

Other Line Costs—Other line costs do not readily lend

themselves to *a priori* engineering estimation. Of these the most important is the construction service charge for laying the line. Such prices are bid prices and are, therefore, to some extent a function of competitive conditions at any given time. The costs used in this study were estimated by a pipe line general contracting company on the basis of actual costs on some forty projects of varying diameters and lengths with which this company has been associated. This construction fee contains allowances for construction materials, *e.g.*, lumber and concrete (or cement). The engineering and labor costs were derived from the same source.

The other important materials costs are those of structural steel and line valves and fittings. These costs were also based on actual cost data provided by the general contractor. While it is possible to compute valve costs if the type and number of valves required can be generalized, it is not possible to make any general statement on the number required on any given line. These valve costs include the cost of large block valves, any fittings used to install them, and the cost of motor operators for the valves. The necessity for installing such valves varies from line to line depending on such things as the number of river crossings (as opposed to the number of miles of river crossings), the number of hills crossed, etc. On the basis of the actual cases covered by the general contractor's data, it would appear that block valves are used on the average about every thirty miles, although the spacing may be irregular; in other words, on the average it would be expected that about 33 main gate valves would be used on a 1000 mile pipe line. On this basis, costs of such valves and fittings were determined by the contractor for each size of line. (It should be noted that these valves do not include the block valves on each side of pumping stations.)

The cost of structural steel, used principally in river crossings, are also derived from actual costs. Other minor costs variant with line diameter are discussed in Section IV.

III. Costs of Horsepower

Total horsepower costs are computed by multiplying costs per station by the number of stations on a given line. The number of stations on each line covered in the study is shown in Table 2 above. The process of computation is to divide the total pressure drop determined from the hydraulic formula by the station operating pressure (the maximum at which the line can be operated) less the station suction pressure (assumed to be 20 p.s.i.). This minimizes the number of stations and hence minimizes costs.

Horsepower costs, unlike line diameter costs, consist of both initial expenditures for building the stations and subsequent expenditures for operating and maintaining them. The remainder of this section will be concerned with a summary description of the computational process for initial and subsequent station costs respectively.

The stations for which costs were computed have the following characteristics. (1) They are of the "semi-automatic" type; that is, automatic controls are used within the stations but the stations are not controlled electronically from a central office. The labor force required is two men per shift.

(2) Electric motors and centrifugal pumps are used. Following what seems to be average industry practice (see Appendix A) stations on lines having throughputs less than 100,000 barrels per day have two full-size pumps (and motors) and one half-size pump (and motor). The two full-size installations can develop the total station horsepower. For throughputs over 100,000 barrels per day, 3½ pumps

and motors are used. This balances the desirability of having flexibility of operation with constant speed motors against the desirability of using more economical large motors (motor prices per horsepower decrease with motor size up to 2000 horsepower).

(3) The stations each include: a pumphouse having a pump room, office, and control room; one auxiliary building containing garage space and the station heating plant; two cottages for housing the station chief and assistant chief; outside power and lighting and a substation; and the necessary site improvements (roads, fences, sewers, etc.).

(4) Each station utilizes in-and-out piping to permit repair of one pump without having to shut down the whole station.

A. *Initial Station Costs*

Initial station costs may be divided into five categories: (1) those common to all stations of a given type; (2) those variant with the *number* of pumps and motors (and hence common to all stations having the same number of pumps and motors); (3) those variant with throughput; (4) those variant with horsepower; and (5) those variant with line diameter. Each of these will be discussed in turn.

Costs Common to All Stations—Table 4 shows the total cost per station of each part of the station which has a cost invariant with either horsepower, the number of pumps, throughput, or line diameter. These parts include outside improvements, water supply, service tanks, cottages, auxiliary buildings, heating plant, etc. The "miscellaneous machinery and equipment" category in Table 4 includes a station intercommunication system, fire protection equipment, office furniture, and machines, tools, etc. The "miscellaneous" category includes principally the station pump system.

Since these costs do not lend themselves readily to *a priori* engineering estimation, they were in general computed from actual costs. The material costs were based on data provided by a pipe line company. These data cover five stations on a recent large-diameter line. Labor costs for site improvements were averaged from two engineering estimates and a set of actual costs. Labor costs for the auxiliary building were computed in the same manner as those for the pumphouse which is discussed below.

TABLE 4

INVARIANT INITIAL STATION COSTS
(1952 Dollars)

	Materials	Labor	Construction Service	Freight	Engineering	Total
Outside Improvements	$30,408	$12,000	$ 6,700	$1,000	—	$ 50,108
Water Supply	16,932	3,600	2,200	—	$100	22,832
Service Tanks	1,120	11,300	1,700	—	—	14,120
Machinery & Equipment	4,122	700	700	—	—	5,522
Employee Housing	13,257	12,700	2,900	—	—	28,857
Auxiliary Building	11,699	8,500	2,300	700	—	23,199
Miscellaneous	5,479	11,800	1,900	—	—	19,179
Total	$83,017	$60,600	$18,400	$1,700	$100	$163,817

Source: See text, page 70.

Cost Variant With Number of Pumps and Motors—The principal item in this category is the pumphouse, the cost of which varies somewhat with the number of pumps and motors installed. To a large extent, pumphouse costs are fixed in respect to the number of units installed; but more units require more floor space, and hence mean higher costs. There would probably be some variation with the *size* of pumps and motors, but this is negligible and may be ignored for the computation of typical costs. (Actual cases were

found where small installations used more floorspace than large.) This study will require only two pumphouse sizes, one for 2½-pump stations and one for 3½-pump stations. Pumphouse costs are summarized in Table 5.

TABLE 5

PUMPHOUSE COSTS

	2½ Pumps	3½ Pumps
Fixed:		
Equipment	$17,000	$17,000
Engineering	3,400	3,400
Variant:		
Materials	16,100	18,500
Labor	25,400	29,200
Construction	7,100	7,800
Freight	1,800	2,100
Total	$70,800	$78,000

Source: See text, pages 71–73.

Pumphouse costs largely invariant with floorspace include plumbing fixtures, overhead crane, exhaust fans (for rooms, not for motors), wiring, etc. These material and equipment costs were determined from actual costs of four stations.

Pumphouse costs variant with the number of units installed include principally the building items which vary with floor space. These costs were computed on the basis of 1200 square feet for the control room and office, and 1800 and 2250 square feet for the pump room for the 2½- and 3½-pump stations respectively. These floor space data were the approximate minimum space provided in eight different station plans for stations built on five recent large-diameter lines. For example, pump room floor space in these stations ranged from 2250-2700 square feet. The smallest figure was used in this study on the theory that if one line can be

operated with this space, others can; any extra space, then, is not essential.

The variant materials cost ($5.85 per square foot) was computed from actual cost data of five stations. The labor costs ($8.45 per square foot) were based on two engineering estimates and actual costs of four stations. The other service costs were estimated from actual costs of four stations. The total costs per cubic foot are $1.74 and $1.68 for 2½- and 3½-pump stations respectively; this may be compared with an average of $1.67 for seven 3½-pump stations which were not used in the computation.

In addition to pumphouse costs, the amount of certain auxiliary equipment items used depends in part on the number of pumps installed. These items include such things as motor and pump foundations, pump and motor control and measuring instruments, the cabinets and panelboards for these instruments, instrument wiring, an air compression system to operate the instruments, foundations for the pumps and motors, etc. These costs amount to $21,563 and $25,393 for 2½- and 3½-pump stations respectively.

Costs Variant With Throughput—The items classified in this category are the main line pumps. In accord with the current industry trend, and because they are cheaper, centrifugal pumps are used. The data were provided by a pump manufacturer. Prices are constant for rather wide ranges of throughputs. Table 6 shows the number of pumps, pump efficiency, and total pump costs for each throughput covered by the study. As was noted above, for purposes of flexibility 2½ pumps are used on lines having throughputs less than 100,000 barrels per day, while 3½ pumps are used on the larger lines. On the advice of a pump company, 3600 RPM pumps were used for throughputs less than 150,000 barrels

per day, while 1800 RPM pumps were used for the larger throughputs.

TABLE 6

PUMP COSTS PER STATION

Throughput (Barrels per Day)	Number of Pumps per Station	Approximate Efficiency (Per Cent)	Total Pump Cost per Station (Dollars)
25,000	2½	74	16,000
50,000	2½	81	16,800
75,000	2½	81	22,800
100,000	3½	81	25,000
125,000	3½	83	25,000
150,000*	3½	80	44,900
200,000	3½	85	49,500
250,000	3½	85	49,500
300,000	3½	86	77,450
350,000	3½	88	77,450
400,000	3½	90	77,450

Note: * At throughputs less than 150,000, 3600 RPM pumps were used. At throughputs of 150,000 and over, 1800 RPM pumps were used.
Source: Provided by a manufacturer of pumps.

Costs Variant With Horsepower—This category includes the main line motors, switchgear, and blowers to cool the motors. Again in accordance with current industry practice, electric motors (constant speed, totally enclosed, base-ventilated) are used to operate the pumps. There are 2½ motors for lines having throughputs less than 100,000 barrels per day and 3½ motors on lines having greater throughputs. The same RPM assumptions were, of course, made for motors as for pumps.

While it is possible to use one type pump for several different stations, it is necessary to compute motor costs for each station. Since motors are available only in discrete sizes, many stations in the end have the same motor costs; however, it was necessary to compute costs for each. The process of computation was as follows: (1) the hydraulic horsepower required for each station (determined in Table 2) was divided by the efficiency at which the pump is operated in order to

get the motor horsepower which must be installed in order to develop the required hydraulic output horsepower; (2) the appropriate actual size of motor available was chosen for the required installed motor horsepower (this must be the next actual size above the required horsepower, since the required throughput could not be achieved for long periods with the next lower size without danger of over-heating). This size of motor was priced in accordance with current price quotations obtained from two principal motor manufacturers. (Approximate averages of these two quotations were used in order to avoid disclosure of individual prices.) The total station motor costs for main line motors were then determined by multiplying the price of the full-size motor by the number of such motors and adding the cost of the half-size motor. Motor costs per station for each line are shown in Table 7.

Blower costs per station depend on the number of motors, since there should be one blower per motor. In addition blower costs vary somewhat with the horsepower rating of the motor, since larger motors generate more heat and hence require more cooling. It was found from a comparison of several actual blower costs and the horsepowers of the motors they cool that blower costs could be approximated by adding a small amount per horsepower to a fixed minimum cost. The computational system used was $290 plus $1.23 per installed horsepower. The appropriate blower costs per station are shown in Table 7. Costs per station were determined by multiplying the blower cost for the main motor by the number of full size motors and adding the cost of the blower appropriate to the half-size motor. These blower costs include the cost of a small motor used to run the fan, since such units are apparently bought as a whole.

Costs of switchgear for large motors are high. The switchgear costs in a pumping station are in the same magnitudes

TABLE 7

MATERIAL COSTS VARIANT WITH HORSEPOWER OR LINE DIAMETER
(1952 Dollars)

Throughput and Outside Diameter		Installed Motor Horse-power	—Materials and Equipment Cost per Station—			
(Barrels per Day)	(Inches)		Motors[a]	Switch-gear	Blowers	Station Piping
25,000	8⅝	1,500	28,800	20,130	1,215	27,683
	10¾	1,150	27,200	15,433	788	30,025
	12¾	1,000	22,300	13,420	764	32,650
50,000	8⅝	3,700	65,900	49,654	1,721	31,837
	10¾	2,250	41,200	30,195	1,388	34,179
	12¾	1,750	33,000	23,485	1,271	36,804
	14	1,750	33,000	23,485	1,271	39,870
	16	1,500	28,800	20,130	1,215	42,593
	18	1,250	29,200	16,775	810	48,714
75,000	8⅝	4,300	74,700	57,706	1,872	35,447
	10¾	3,200	56,900	42,944	1,607	37,789
	12¾	3,100	55,300	41,602	1,584	40,414
	14	2,500	45,400	33,550	1,445	43,480
	16	2,250	41,200	30,195	1,388	46,203
	18	2,000	37,200	26,840	1,330	52,324
	20	1,750	33,000	23,485	1,271	60,507
	22	1,500	28,800	20,130	1,215	65,465
100,000	10¾	4,350	74,200	58,377	2,162	42,872
	12¾	3,150	57,400	42,273	1,885	45,497
	14	3,150	57,400	42,273	1,885	48,563
	16	2,800	51,900	37,576	1,804	51,286
	18	2,450	46,100	32,879	1,724	57,407
	20	2,100	40,300	28,182	1,643	65,590
	22	2,100	40,300	28,182	1,643	70,548
	24	1,750	39,000	23,485	1,215	74,391
	26	1,600	37,600	21,472	1,182	88,186
125,000	12¾	4,350	74,200	58,377	2,162	45,497
	14	3,500	63,200	46,970	1,965	48,563
	16	3,150	57,400	42,273	1,885	51,286
	18	2,800	51,900	37,576	1,804	57,407
	20	2,450	46,100	32,879	1,724	65,590
	22	2,450	46,100	32,879	1,724	70,548
	24	2,100	40,300	28,182	1,643	74,391
	26	2,100	40,300	28,182	1,643	88,186
	30	1,750	39,000	23,485	1,215	99,092
150,000	14	4,450	49,700	59,719	2,185	63,921
	16	4,350	48,800	58,377	2,162	66,644
	18	3,500	40,900	46,970	1,965	72,765

TABLE 7—(*continued*)

Throughput and Outside Diameter (Barrels per Day)	(Inches)	Installed Motor Horsepower	—Materials and Equipment Cost per Station— Motors[a]	Switchgear	Blowers	Station Piping
	20	3,150	37,600	42,273	1,885	80,948
	22	2,800	34,400	37,576	1,804	85,906
	24	2,800	34,400	37,576	1,804	89,749
	26	2,450	30,800	32,879	1,724	103,544
	30	2,100	27,400	28,182	1,643	114,450
	32	2,100	27,400	28,182	1,643	138,296
200,000	16	5,200	57,700	69,784	2,356	76,575
	18	4,450	49,700	59,719	2,185	82,696
	20	4,350	48,800	58,377	2,162	90,879
	22	3,500	40,900	46,970	1,965	95,837
	24	3,150	37,600	42,273	1,885	99,680
	26	3,150	37,600	42,273	1,885	113,475
	30	2,800	34,400	37,576	1,804	124,381
	32	2,450	30,800	32,879	1,724	129,881
250,000	18	6,050	66,300	81,191	2,571	91,111
	20	5,200	57,700	69,784	2,356	99,294
	22	4,450	49,700	59,719	2,185	104,252
	24	4,350	48,800	58,377	2,162	108,095
	26	4,350	48,800	58,377	2,162	121,890
	30	3,200	38,200	42,944	1,896	132,796
	32	3,150	37,600	42,273	1,885	138,296
300,000	20	6,150	67,200	82,533	2,594	99,522
	22	5,300	58,800	71,126	2,379	104,480
	24	5,200	57,700	69,784	2,356	108,323
	26	4,450	49,700	59,719	2,185	122,118
	30	4,350	48,800	58,377	2,162	133,024
	32	3,500	40,900	46,970	1,965	138,524
350,000	22	6,150	67,200	82,533	2,594	104,480
	24	6,050	66,300	81,191	2,571	108,323
	26	5,300	58,800	71,126	2,379	122,118
	30	4,450	49,700	59,719	2,185	133,024
	32	4,350	48,800	58,377	2,162	138,524
400,000	24	6,150	67,200	82,533	2,594	108,323
	26	6,050	66,300	81,191	2,571	122,118
	30	5,200	57,700	69,784	2,356	133,024
	32	5,200	57,700	69,784	2,356	138,524

Note: a-2½ Motors for throughputs less than 100,000 barrels per day; 3½ Motors for larger throughputs.

Source: See text, pages 74–75 and 78–81.

as the motor costs themselves. Switchgear costs are roughly proportional to installed horsepower of the motors, at least in the ranges of station horsepower covered in this study. Since there is no relatively simple way of estimating switchgear costs on an *a priori* engineering basis, an investigation was made of actual switchgear costs on four recent long crude lines (one 26-inch, one 24-inch, one 22-inch, and one 18-inch). The total installed horsepower on these lines (ranging from 14,209 horsepower to 22,800 horsepower), their total switchgear costs, and the resulting costs per horsepower of switchgear are shown in Table 8.

TABLE 8

SWITCHGEAR COSTS
(1952 Dollars)

	Total Installed Motor HP*	Total Switchgear Cost*	Switchgear Cost per HP
Pipe Line "A"	14,209	$192,248	$13.53
Pipe Line "B"	22,800	296,570	13.01
Pipe Line "C"	21,750	313,298	14.40
Pipe Line "D"	19,950	255,000	12.75
Average			$13.42

Note: * Sum of all stations.

The service costs of installing the pumping equipment are as follows:

SERVICE COSTS OF INSTALLING PUMPING EQUIPMENT
(1952 Dollars)

	2½ Pumps	3½ Pumps
Labor	$12,300	$16,400
Construction Service	10,900	14,600
Freight	1,600	2,100
Engineering	2,900	3,900
Total	$27,700	$37,000

Costs Variant With Line Diameter—Some of the initial outlays for stations vary in part with line diameter. These encompass the costs of station piping. This is oil piping, as opposed to piping for the sewer and pump systems, which have been covered above. The station piping may be divided into two categories: (1) piping around the pumps; and (2) piping at the connection to the main line. The term "piping" includes pipe, valves, fittings, motor operators for the valves, and wiring for the operators.

(1) Pump Piping: The stations on these lines use "in and out" piping to permit maintenance operations on individual pumps without closing down the station. That is, each pump will be connected in such a way that it can be by-passed without shutting down the station. This system is depicted in Figure 3 below.

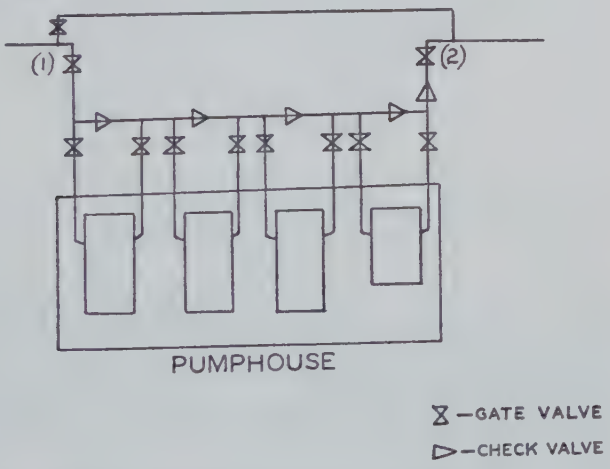


FIGURE 3. "In and Out" Pump Piping.

Pump piping costs include the costs of all valves, fittings, motor operators, and the pipe from valve (1) to valve (2) in Figure 3. The equipment costs for pump piping were deter-

mined by aggregating the number of valves, operators, reducers, tees, etc. needed in appropriate sizes and pricing according to principal manufacturers' price quotations. The appropriate sizes were determined by the size of the intake opening on the pumps. There were six such sizes used; this necessitated the computation of six sets of pump piping costs. Since these costs depend on the size of the pumps, which in turn depends on throughput, pump piping costs may be said to vary with throughput.

(2) Connection piping costs cover the block and connecting valves and fittings which join the station to the main line and the scraper trap and its fittings (a "scraper trap" is a piping system used to insert a cleaning device, called a

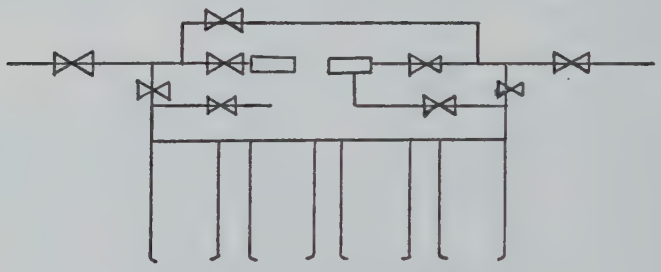


FIGURE 4. Connection Piping.

"pig," in the line). Connection piping is illustrated in Figure 4. The process of computation of equipment costs was the same as for pump piping. It is the connection pipe costs which vary with line diameter, since they depend on the size of the main line.

Since total pipe costs vary with both line diameter and throughput, there is a different pipe cost per station for each line covered in the study. The material costs are shown in Table 7 above.

The service costs of installing piping are as follows:

SERVICE COSTS OF INSTALLING PIPING
(1952 Dollars)

	2½ Pumps	3½ Pumps
Labor	$21,200	$26,500
Construction Service	1,000	1,300
Freight	2,000	2,800
Engineering	100	100
Total	$24,300	$30,700

Summary—Total initial costs per station and per 1000 miles are shown in Table 9.

B. *Subsequent Station Operating Costs*

Station operating costs incurred subsequent to the building of the line are much more important in relation to total cost than are initial station costs. The subsequent costs are, however, more readily computed. It is ironic in pipe line costing that the item requiring the most effort, *viz.*, initial station costs, is not of major importance (relative to total costs) on economic lines. There are three major subsequent station cost items. In order of importance they are the costs of electric power, labor, and maintenance.

Electric Power Costs—Annual electric power costs per station for capacity operation of each line were computed by the following process. (1) Required station hydraulic horsepower (see Table 2) was divided by pump efficiency (see Table 6), motor efficiency (assumed to average 94 per cent), and coupling efficiency (assumed to average 98 per cent) in order to determine the required horsepower input for producing the necessary hydraulic horsepower output.

TABLE 9

INITIAL STATION COSTS PER STATION AND PER 1000 MILES
(1952 Dollars)

Throughput and Outside Diameter (Barrels per Day)	(Inches)	Total Cost per Station (Dollars)	Number of Stations per 1000 miles	Total Station Capital Cost per 1000 miles ($000)
25,000	$8\frac{5}{8}$	424,411	12.06	5,100.3
	$10\frac{3}{4}$	420,029	5.02	2,101.0
	$12\frac{3}{4}$	415,717	2.57	1,064.5
50,000	$8\frac{5}{8}$	496,495	30.15	14,924.1
	$10\frac{3}{4}$	454,345	16.71	7,567.0
	$12\frac{3}{4}$	441,943	8.55	3,765.7
	14	445,009	5.93	2,630.0
	16	440,121	3.52	1,543.9
	18	442,882	2.23	984.3
75,000	$8\frac{5}{8}$	523,108	81.13	42,318.1
	$10\frac{3}{4}$	492,623	33.76	16,580.3
	$12\frac{3}{4}$	492,283	17.27	8,475.8
	14	477,258	11.99	5,704.3
	16	472,369	7.12	3,352.6
	18	471,077	4.51	2,117.8
	20	471,646	3.02	1,419.8
	22	468,993	2.10	981.7
100,000	$10\frac{3}{4}$	559,946	55.62	31,060.8
	$12\frac{3}{4}$	529,390	28.45	15,018.5
	14	532,456	19.76	10,491.7
	16	524,901	11.73	6,139.5
	18	520,445	7.44	3,861.0
	20	518,050	4.98	2,572.4
	22	523,008	3.46	1,804.4
	24	520,426	2.48	1,286.9
	26	530,775	1.83	968.6
125,000	$12\frac{3}{4}$	562,571	41.88	23,497.1
	14	543,033	29.10	15,758.6
	16	535,179	17.27	9,216.6
	18	531,022	10.95	5,798.3
	20	528,628	7.34	3,869.1
	22	533,586	5.09	2,708.3
	24	526,851	3.66	1,922.8
	26	540,646	2.69	1,450.3
	30	545,127	1.57	853.5

TABLE 9—(*continued*)

Throughput and Outside Diameter (Barrels per Day)	(Inches)	Total Cost per Station (Dollars)	Number of Stations per 1000 miles	Total Station Capital Cost per 1000 miles ($000)
150,000	14	577,760	39.93	23,010.1
	16	578,218	23.75	13,697.1
	18	564,835	15.06	8,483.8
	20	564,941	10.09	5,685.1
	22	561,921	7.00	3,922.9
	24	565,764	5.03	2,838.2
	26	571,182	3.70	2,107.8
	30	573,910	2.15	1,230.7
	32	597,756	1.69	1,007.8
200,000	16	613,250	39.03	23,876.6
	18	601,135	24.75	14,841.0
	20	607,053	16.58	10,040.1
	22	592,507	11.50	6,796.6
	24	588,273	8.27	4,852.6
	26	602,068	6.08	3,651.5
	30	604,996	3.54	2,136.4
	32	602,119	2.78	1,669.7
250,000	18	648,008	36.45	23,565.2
	20	635,969	24.42	15,493.7
	22	622,691	16.94	10,532.0
	24	624,269	12.17	7,579.1
	26	638,064	8.96	5,703.6
	30	622,671	5.22	3,242.5
	32	626,889	4.09	2,557.8
300,000	20	686,634	33.50	22,952.0
	22	671,570	23.24	15,572.4
	24	672,948	16.70	11,213.2
	26	668,507	12.29	8,197.5
	30	677,148	7.16	4,837.6
	32	663,144	5.61	3,711.8
350,000	22	691,592	30.37	20,958.1
	24	693,170	21.82	15,092.2
	26	689,208	16.06	11,046.6
	30	679,413	9.35	6,338.5
	32	682,648	7.33	4,992.8
400,000	24	695,435	27.51	19,090.2
	26	706,965	20.25	14,285.7
	30	697,649	11.79	8,207.6
	32	703,149	9.25	6,490.3

Source: Section III-A.

(2) This power input per station was priced by converting to kilowatt hours per year and multiplying by eight mills per KWH, thereby giving power cost per station per year.

(3) Cost per station was converted to cost per line by multiplying by the number of stations on each line (see Table 2).

Costs per station for capacity operation are shown in Table 10; costs per line are shown in Table 11. These power costs are, of course, not applicable to all pipe lines, since prices of electric power vary from region to region. In any given actual situation, should power costs be higher it would be economical to use larger (outside-diameter) pipe than indicated in Section V and fewer stations. In addition, one-, two-, or perhaps three-stage telescoping might become the economic piping program, since steel would be substituted for stations in the computations in Section I.

Operating Labor Costs—A labor crew consisting of a station chief engineer, an assistant chief engineer, six operating engineers, and one yard and general utility man was selected for each station. Such a crew is necessary for three-shift operation with two men on duty each shift (eight men working a basic 40-hour week, with a 48-hour week for two of the eight each week). It will be recalled that the stations used in this study are the "semi-automatic" type in which all pumping equipment is controlled from the control room (as opposed to having either manually operated valves at stations operated from a central control office by electronic equipment). Two operating men are needed on each shift, one, say, to operate the station controls (pumps, motors, piping, and tanks), while the other is available for any maintenance, communication, or other duties that might have to be performed.

TABLE 10

ANNUAL ELECTRIC POWER COSTS PER STATION
(1952 Dollars)

Throughput (Barrels per Day)	Outside Diameter (Inches)	Station HP	Annual Power Cost per Station (Capacity Operation) ($000)
25,000	8⅝	813	62.35
	10¾	650	49.85
	12¾	546	41.87
50,000	8⅝	2,165	151.69
	10¾	1,300	91.08
	12¾	1,093	76.58
	14	994	69.64
	16	871	61.03
	18	774	54.23
75,000	8⅝	2,439	170.89
	10¾	1,951	136.69
	12¾	1,640	114.90
	14	1,491	104.47
	16	1,305	91.43
	18	1,160	81.27
	20	1,038	72.73
	22	940	65.86
100,000	10¾	2,601	182.24
	12¾	2,186	153.16
	14	1,987	139.22
	16	1,740	121.91
	18	1,544	108.18
	20	1,382	96.83
	22	1,253	87.79
	24	1,147	80.36
	26	1,056	73.99
125,000	12¾	2,734	186.94
	14	2,484	169.85
	16	2,176	148.79
	18	1,932	132.10
	20	1,727	118.09
	22	1,568	107.21
	24	1,431	97.85
	26	1,322	90.39
	30	1,137	77.74

TABLE 10—(*continued*)

Throughput (Barrels per Day)	Outside Diameter (Inches)	Station HP	Annual Power Cost per Station (Capacity Operation) ($000)
150,000	14	2,981	211.47
	16	2,611	185.22
	18	2,318	164.44
	20	2,073	147.06
	22	1,882	133.51
	24	1,719	121.95
	26	1,587	112.58
	30	1,370	97.19
	32	1,278	90.66
200,000	16	3,482	232.48
	18	3,091	206.38
	20	2,764	184.54
	22	2,510	167.59
	24	2,290	152.90
	26	2,116	141.28
	30	1,823	121.72
	32	1,704	113.78
250,000	18	3,864	257.99
	20	3,455	230.68
	22	3,137	209.45
	24	2,865	191.29
	26	2,644	176.53
	30	2,276	151.96
	32	2,129	142.15
300,000	20	4,147	273.66
	22	3,764	248.39
	24	3,438	226.88
	26	3,173	209.39
	30	2,732	180.29
	32	2,556	168.67
350,000	22	4,391	283.18
	24	4,011	258.67
	26	3,702	238.75
	30	3,189	205.66
	32	2,982	192.31
400,000	24	4,584	289.06
	26	4,230	266.74
	30	3,645	229.85
	32	3,405	214.71

Source: See text, pages 81 and 84.

TABLE 11

TOTAL ANNUAL WAGE, POWER, AND MAINTENANCE COSTS
(1952 Dollars)

Through-put	Line Diameter	Horse-Power (Capacity Operation)	Wages	Main-tenance	Total
			.....$000.....		
25,000	8⅝	751.9	566.8	77.8	1,396.5
	10¾	250.2	235.9	32.4	518.5
	12¾	107.6	120.8	16.6	245.0
50,000	8⅝	4,573.5	1,417.0	194.5	6,185.0
	10¾	1,521.9	785.4	107.8	2,415.1
	12¾	654.8	401.9	55.1	1,111.8
	14	413.0	278.7	38.2	729.9
	16	214.8	165.4	22.7	402.9
	18	120.9	104.8	14.4	240.1
75,000	8⅝	13,864.3	3,813.1	523.3	18,200.7
	10¾	4,614.7	1,586.7	217.8	6,419.2
	12¾	1,984.3	811.7	111.4	2,907.4
	14	1,252.6	563.5	77.3	1,893.4
	16	651.0	334.6	45.9	1,031.5
	18	366.5	212.0	29.1	607.6
	20	219.6	141.9	19.5	381.0
	22	138.3	98.7	13.5	250.5
100,000	10¾	10,136.2	2,614.1	478.3	3,228.6
	12¾	4,357.4	1,337.1	244.7	5,939.2
	14	2,751.0	928.7	169.9	3,849.6
	16	1,430.0	551.3	100.9	2,082.2
	18	804.9	349.7	64.0	1,218.6
	20	482.2	234.1	42.8	759.1
	22	303.8	162.6	29.8	496.2
	24	199.3	116.6	21.3	337.2
	26	135.4	86.0	15.7	237.1
125,000	12¾	7,829.0	1,968.3	360.2	10,157.5
	14	4,942.6	1,367.7	250.3	6,560.6
	16	2,569.6	811.7	148.5	3,529.8
	18	1,446.5	514.7	94.2	2,055.4
	20	866.8	345.0	63.1	1,274.9
	22	545.7	239.2	43.8	828.7
	24	358.1	172.0	31.5	561.6
	26	243.1	126.4	23.1	392.6
	30	122.1	73.8	13.5	209.4

TABLE 11—(*continued*)

Through-put	Line Diameter	Horse-Power (Capacity Operation)	Wages	Main-tenance	Total
150,000	14	8,444.0	1,876.7	343.4	10,664.1
	16	4,399.0	1,116.3	204.3	5,719.6
	18	2,476.5	707.8	129.5	3,313.8
	20	1,483.8	474.2	86.8	2,044.8
	22	934.6	329.0	60.2	1,323.8
	24	613.4	236.4	43.3	893.1
	26	416.5	173.9	31.8	622.2
	30	209.0	101.1	18.5	328.6
	32	154.9	79.4	14.5	248.8
200,000	16	9,073.7	1,834.4	335.7	11,243.8
	18	5,107.9	1,163.2	212.9	6,484.0
	20	3,059.7	779.3	142.6	3,981.6
	22	1,927.3	540.5	98.9	2,566.7
	24	1,264.5	388.7	71.1	1,724.3
	26	859.0	285.8	52.3	1,197.1
	30	430.9	166.4	30.4	627.7
	32	316.3	130.7	23.9	470.9
250,000	18	9,403.7	1,713.2	313.5	11,430.4
	20	5,633.2	1,147.8	210.0	6,991.0
	22	3,548.1	796.2	145.7	4,490.0
	24	2,328.0	572.0	104.7	3,004.7
	26	1,581.7	421.1	77.1	2,079.9
	30	793.2	245.3	44.9	1,083.4
	32	581.4	192.2	35.2	808.8
300,000	20	9,167.6	1,574.5	288.1	11,030.2
	22	5,772.6	1,092.2	199.9	8,064.7
	24	3,788.9	784.9	143.6	4,717.4
	26	2,573.4	577.6	105.7	3,256.7
	30	1,290.0	336.5	61.6	1,689.0
	32	946.2	263.7	48.2	1,258.1
350,000	22	8,600.2	1,427.4	261.2	10,288.8
	24	5,644.2	1,025.5	187.7	6,857.4
	26	3,834.3	754.8	138.1	4,727.2
	30	1,922.9	439.4	80.4	2,442.7
	32	1,409.6	344.5	63.0	1,817.1
400,000	24	7,952.0	1,293.0	236.6	9,481.6
	26	5,401.5	951.8	174.2	6,527.5
	30	2,709.9	551.1	101.4	3,362.4
	32	1,986.1	434.8	79.6	2,500.5

Source: Section III-B.

Each station requires the same size crew regardless of its horsepower capacity. Of course if the horsepower were increased to very high levels with, say, twice as many motors, then one or two more men might be needed on each shift. Mr. Hughes in his thesis added a man to stations having more than 2400 horsepower[5] (with diesel engines). However, it would appear that the *number* of motors (and pumps) is more important than the installed horsepower of the station in determining the number of workers necessary. Doubling the number of pumps and motors would also double the number of pump piping valves and would increase the number of controls to be watched by the operator; furthermore, it would mean twice as many pumps, motors, blowers, and pump piping valves to maintain. On the other hand, simply raising the horsepower of each of three or four motors does none of these things. In any event, one known large pipe line with stations of 4750 installed horsepower each, utilizes two-man shifts.

The labor costs were computed on the basis of the following annual salaries: station chief, $6,250; assistant chief, $5,750; six operators, $5,250 each; yard man, $3,500—giving a total annual wage bill per station of $47,000. The total station labor costs for each line are indicated in Table 11 (any one cost was determined by multiplying the annual station wage bill by the appropriate number of stations). These annual wages were based on 1951 salary data published by the Interstate Commerce Commission.[6] Average 1951 wages were computed by dividing the ICC data on total payments to selected classes of employees (covering all lines operating in interstate commerce) by the number of such employees. The 1951 wages were then inflated to 1952 dollars by the percentage change in the Bureau of Labor

Statistics wage series for oil company workers (refinery workers, since the BLS releases no series on pipe line employees). This computation is summarized below:

Employee	ICC 1951 Average Wage	Wage in 1952 Dollars	Figure Used in Study
Foremen	$5,515	$5,967	$6,000*
Station Engineers	4,834	5,263	5,250
Laborers	3,255	3,521	3,500

* The chief station engineer was entered at $6,250, while the assistant chief was entered at $5,750.

Maintenance Expenditures—Maintenance expenditures are of minor importance relative to those for power and labor costs. Consequently, only one source was used for maintenance costs. The costs used were based on actual expenditure data provided to Mr. J. H. Sybert by the Magnolia Petroleum Company in 1947.[7] Mr. Sybert's actual costs were inflated in approximately the same proportions as the increase in the BLS series on electrical machinery prices (an increase of about 21 per cent).

Maintenance expenditures cover repair materials for the station equipment, lubricants, parts, etc. (not maintenance labor, which is covered by the station labor computation). These expenditures might be expected to vary somewhat with the size of pumps and motors, as well as with the numbers thereof. A given part for a large motor might cost somewhat more than the same kind of part for a small motor. However, the principal variation would be caused by the *number* of motors and pumps (and hence of pump piping valves, blowers, controls, etc.) serviced. The maintenance costs were therefore computed on the basis of $2,150 per pump per year. This might understate slightly for motors larger than those used as the basis for computation (600 HP)

and overstate slightly for smaller motors. However, all stations in the study have the same number of certain items (*e.g.*, some pumping controls, connecting piping valves, etc.); to this extent maintenance costs for both sizes of stations would tend to be the same. Because of these offsetting variations it was not felt to be too unreasonable simply to vary maintenance costs with the number of pumps and motors. At $2,150 per pump per year, annual costs would be $6,450 and $8,600 for 2½- and 3½-pump stations respectively. Total annual maintenance costs for each line are shown in Table 11 above. These were determined by multiplying the cost per station by the appropriate number of stations.

Summary—Total annual subsequent station operating expenditures are shown in Table 11.

IV. Miscellaneous Costs

Before proceeding to the determination of the optimum line size in Section V, it is necessary to compute costs of items which vary with neither horsepower nor line diameter in order that these miscellaneous costs may be added to the least expenditures for the two principal composite factors of production. Miscellaneous costs, like horsepower costs, fall into two categories: initial outlays and subsequent annual expenditures. In this case, however, it is the initial outlays which are more important. Some of the costs to be discussed in this section depend on length of line or throughput; others are almost invariant regardless of the length, diameter, or throughput of a line.

A. *Initial Miscellaneous Costs*

The principal initial costs invariant with horsepower or line diameter are the costs of a communication system, sur-

veying the right-of-way, damages to land crossed, tankage, and the final terminal.

Communication System—The lines in this study are equipped with a microwave communication system. The cost of such a system depends upon the length of the line. Table 12 indicates the approximate per mile costs of such a system. The total cost for a 1,000-mile line is some 700 thousand dollars. These costs are based on actual costs from several recent projects. They assume an average tower spacing of 30 miles (175-foot towers) and a twelve channel communication system.

TABLE 12

MICROWAVE COMMUNICATIONS COST FOR 1,000-MILE PIPE LINE

Item	Total Cost	Cost per Mile
Engineering and Test	$ 42,000	$ 42.00
Emergency Power (Generators)	70,000	70.00
Buildings and Fences	70,000	70.00
Towers	84,000	84.00
Channeling Equipment	70,000	70.00
Radio Equipment	364,000	364.00
Total	$700,000	$700.00

Source: See text, page 92.

Surveying and Damages—Costs of surveying the right-of-way and the payment of damages and right-of-way fees to land owners would not be expected to vary with either line diameter or horsepower. Data from a pipe line general contractor (see Section II), indicate an average cost per mile for surveying of $400, but show damages and right-of-way expenditures which increase with diameter. The latter assumption was rejected upon the advice of other industry sources. The figure chosen for this study is that indicated by the contractor for the middle size of pipe, *viz.*, $1,760 per

mile. This cost plus the surveying cost gives an average cost per mile of $2,160, and an average cost per 1000-mile line of $2,160 thousand.

This may be compared with the corresponding cost per mile of two recent large-diameter lines (aggregating 1720 miles): $2,209 per mile. A larger number of actual costs was not available because five of the principal recent projects were built on existing rights of way, thereby eliminating the necessity of making extensive surveys and right-of-way payments (damage costs, of course, would be incurred even on these lines).

Tankage—Another initial cost of considerable importance is that of tankage (tank costs are of the same magnitude as initial station costs on larger economic lines). Tankage costs would be expected to depend primarily on the throughput of the line. The larger the throughput, the more tankage is needed at the beginning and end of the line and along the line in case of breakage. In addition, tankage costs also depend to some extent upon the number of companies owning the line, the kind of crude shipped, and the length of the line. The more companies which own the line, the more tanks will be needed at the originating station—if each company demands separate shipment of its oil. However, if the companies utilize common stream shipment, then it is not so necessary that each have its own inventories on the site at all times. If several kinds of crude are shipped, then more tankage is required. If the line is very long, then somewhat more tankage will be needed simply because there are more miles of pipe and hence more places for breaks; on the other hand, some lines use no tanks at all along the line (*e.g.*, Interprovincial). In spite of these factors, the basic determinant of tankage is apparently throughput; all tankage

costs in this study were a function of throughput. Some allowance for other factors was automatically made, since a capacity-throughput relation was determined from averaging actual cases.

In order to determine the relationship between tankage and throughput, an investigation was made of working tank capacity on nine major trunk lines (see Table 13). The number of days' supply of storage capacity (throughput per day divided by working tank storage capacity) for these lines ranges from 11.90 days to 23.90 days. However, seven out of nine lines have between 11.90 and 12.90 days' supply. The arithmetic mean of these seven is 12.43 days' supply. The mean of all nine lines is 13.95 days; the median of all nine is 12.62 days. It was decided to use a figure equal to 12.5 times the throughput of the line for average total tankage capacity.

Knowing total tankage capacity is, however, not sufficient for the determination of tankage costs. The cost per barrel of capacity of a tank decreases with the size of the tank because of the volume-area relationship. It is, therefore, necessary to know either the average cost of various lines for tankage in relation to their capacity or an average size of tank. The former figure was not available; from such actual data as were available it was found that a 55,000-barrel tank was formerly most representative of the size used on trunk lines along the line. However, the current tendency is to utilize large tanks at terminal tank farms and in some cases along the line. Not only are they cheaper per barrel of capacity, but some companies seem to feel that they give less operating difficulty. Furthermore, less auxiliary equipment (*e.g.*, switches, valves, etc.) is needed with a small number of large tanks than with a large number of small tanks. Typical costs

per barrel of several common sizes of tanks are shown in Table 14.

TABLE 13

ACTUAL TANKAGE CAPACITY
Nine Large Crude Lines

	Tankage Capacity (Barrels)	Initial Throughput Capacity (Barrels per Day)	Days' Supply of Storage Capacity
	.....000's.....		
Pipe Line "A"	1,030	84	12.26
Pipe Line "B"	3,868	325	11.90
Pipe Line "C"	2,698	209	12.90
Pipe Line "D"	2,024	157	12.89
Pipe Line "E"	840	70	12.00
Pipe Line "F"	3,785	300	12.62
Pipe Line "G"	2,390	100	23.90
Pipe Line "H"	3,490	280	12.46
Pipe Line "I"	2,446	167	14.65
Average			13.95
Average excluding Line "G" and Line "I"			12.43

Source: Derived from trade journal reports and information obtained from private sources.

TABLE 14

TYPICAL TANKAGE COSTS FOR COMMON SIZES OF FLOATING ROOF TANKS

Capacity	Tank Cost per Barrel*
55,000	$1.00
80,000	.95
120,000	.90
150,000	.90

Note: * Includes tank proper and erection labor.
Source: Computed from prices quoted by a floating roof tank manufacturer.

An average of $.95 was chosen, since costs on the larger tanks are about constant and since some consideration should be given to the smaller tanks. This average is made up of

$.570 for the tank and $.380 for erection labor. In addition, tank costs should include allowances for foundations and paint. The corresponding costs per barrel are: $.0175 for foundations, $.0260 for painting labor, and $.0065 for paint. The total per barrel from these data is $1.000. That the total per barrel costs add up to $1.000 is the result of coincidence, not premeditation. These figures may be compared with actual costs on two recent projects of $0.94 and $1.02.

In addition to tank costs proper, it is necessary to include costs of lines connecting the tanks to the main line, valves, wiring for the operators, etc. An average of $0.3436 per barrel of tank capacity based on actual costs from three recent large-diameter crude lines was used for these items.

One other minor cost associated with tanks must be noted, *viz.*, land costs. The average size tank used was 80,000 barrels. Such a tank has a diameter of about 115 feet. In accord with information furnished by the tank company which furnished the tank prices, approximately two diameters will be assumed between tanks. This would mean 2.75 acres per tank, or 2.75/80,000 acres per barrel of tank capacity. For the various throughputs used, tank land costs would be as follows at $100 per acre:

Throughput (Barrels per day)	*Tank Land Cost*
25,000	$ 1,074
50,000	2,148
75,000	3,223
100,000	4,297
125,000	5,371
150,000	6,445
200,000	8,594
250,000	10,742
300,000	12,891
350,000	15,039
400,000	17,188

Total tankage costs for the various throughputs used are shown in Table 15.

TABLE 15

SUMMARY OF TANK COSTS
(1952 Dollars)

Throughput (Barrels per Day)	Tanks	Lines and Manifolds	Total
25,000	$ 312,500	$ 107,375	$ 419,875
50,000	625,000	214,750	839,750
75,000	937,500	322,125	1,259,625
100,000	1,250,000	429,500	1,679,500
125,000	1,562,500	536,875	2,099,375
150,000	1,875,000	644,250	2,519,250
200,000	2,500,000	859,000	3,359,000
250,000	3,125,000	1,073,750	4,198,750
300,000	3,750,000	1,288,500	5,038,500
350,000	4,375,000	1,503,250	5,878,250
400,000	5,000,000	1,718,000	6,718,000

Source: See text, pages 93–96.

End Terminal—The final terminal was assumed to include a manifold containing five valves the size of the main line from which oil may be distributed to the various owners or shippers using the line. In addition the manifold was assumed to have connections to such tankage as may be located at the terminal (all tankage costs were covered in the immediately preceding paragraphs). Finally, there should be a combination warehouse-control building housing the valve controls; this building was assumed to have 1,000 square feet of floorspace of the same construction used for the station pump houses.

The costs of part of a terminal are fixed regardless of the line size. These costs amount to $67,000 (based on two recent projects); these are shown for the lines of the sizes used in the study in Table 16. Certain costs, notably the main

line valves, vary with line diameter. Since they influence the choice of optimum line size, these costs are included in the summary table (Table 3) in Section II.

TABLE 16

TERMINAL COSTS INVARIANT WITH LINE DIAMETER
(1952 Dollars)

Materials	$29,762
Freight	400
Engineering	400
Labor	33,400
Construction	2,990
Total	$66,952

Source: See text, page 97.

Minor Items—Finally there are certain minor items, the costs of which vary principally with the length of the line. On the basis of accounting records of a recent project, such construction materials as sand and gravel, fence posts, culverts, etc., were found to amount to the inconsequential sum of $23,100 per 1,000-mile line. Other minor items consumed by the construction crews amount (at ten spreads per 1,000-mile line) to some $4,900, plus the cost of pigs. This cost varies with the diameter of the line. Hence the pig costs for each line size are included in Table 3 with other costs variant with line diameter.

Summary—The initial costs computed in this section, exclusive of some terminal costs and pig costs, are summarized by throughputs in Table 17.

B. *Subsequent Line Operating Costs*

The final costs to be discussed are subsequent annual operating expenses for a central office, the final terminal, the

TABLE 17

MISCELLANEOUS INITIAL COSTS INVARIANT WITH LINE DIAMETER OR HORSEPOWER
(1952 Dollars)

Throughput (Barrels per Day)	Total Miscellaneous Cost ($000's)
25,000	$3,376
50,000	3,797
75,000	4,218
100,000	4,639
125,000	5,059
150,000	5,480
200,000	6,323
250,000	7,162
300,000	8,007
350,000	8,848
400,000	9,690

Source: See text, Section IV-A.

communication system, and the tank farms. These expenditures cover the salary costs of a central office staff which supervises the whole pipe line, the labor costs of operating the final terminal (utilizing a crew similar to that used on each station), costs of aerial survey of the line for leaks, and labor and material costs of maintaining the line, tank farms, and communication systems. These costs are either fixed regardless of line size or length (office expenses) or proportional to length of line (*e.g.*, line maintenance and aerial survey). They are summarized in Table 18.

The costs of these items are again based on data from Mr. Sybert's thesis, inflated to 1952 dollars.[8] These expenditures are the same for all lines covered by the study; they perforce result in decreasing costs as throughput is increased.

TABLE 18

ANNUAL OPERATING COSTS OTHER THAN STATION OPERATING COSTS
(1,000-mile line—1952 Dollars)

Aerial Survey	$ 14,000
Line Maintenance	200,000
Tank Maintenance	15,000
Communications Maintenance	4,000
Terminal Labor Costs	46,500
Office Expense	40,000
Total	$314,000

Source: See footnote 8.

V. COST CURVES

It is now possible to determine the aggregate costs of carrying crude oil in trunk lines. This will be done here by arithmetic aggregation.

The principal problem involved in combining the costs described in sections II-IV is the reconciliation of annual expenditures for labor, power, maintenance, etc., with the initial outlay for capital equipment. It will be recognized that, say, annual costs cannot be determined by adding one year's wage-power-maintenance bill to the initial outlay, since the capital equipment will last many years. Hence in order to determine annual costs (or costs for any other period), it is necessary to allocate part of the initial cost to each year of operation. This, in turn, necessitates the prediction of the length of life of the capital equipment.

Note that this prediction is critical if it is possible to vary the proportions of the factors of production used for a given output. The length of life influences the relative amounts of money spent initially and subsequently. In general, if a short period is predicted, capital equipment becomes more

expensive per year of operation than if a long period were predicted. This means that subsequent expenditures for labor, power, maintenance, etc., would be substituted for initial expenditures on capital equipment. Indeed, it can be shown that if the wrong life is predicted, the firm will spend inevitably more money than is necessary. This problem can better be described in terms of the economic production function analysis outlined in Section I.

Following that analysis, the expenditure for producing a given level of output with two factors of production is given by:

$$E = P_L L + P_C C,$$

where E is the expenditure, P_L is the price of labor, L is the amount of labor, P_C is the price of capital, and C is the amount of capital.

The annual price of labor is simply a wage rate per man-hour multiplied by the number of hours worked per man per year. The annual price of capital, however, is some *fraction* of the initial cost of a unit of capital. This fraction contains allowances for annual interest payments, property taxes, rent (if any), and amortization (called "depreciation") of the initial outlay.

It will be recalled from Section I that the choice of the optimum economic combination of the physically acceptable possibilities depends on the relative prices of labor and capital. If the price of capital should rise relative to that of labor, then in the long-run labor would be substituted for capital. This is precisely what would (or at least, should) happen in designing a new plant if a firm first predicted a long life and then changed its mind in favor of an estimated short life. The annual price of capital in the former case

would be a smaller figure than that in the latter, since the initial price per unit of capital equipment would be divided by a larger rather than a smaller number of years. For example, an investment amortized over 25 years in equal annual parts would give an annual price of capital (ignoring interest, taxes, etc.) of 4 per cent of the initial outlay. If amortized over five years, the corresponding fraction would be 20 per cent per year. Consequently, on an annual basis, capital in the short-life case is more expensive than in the long-life case; but note that the annual price of labor does not change with changes in the life of the firm. As a result, the change in the assumption regarding the life of the firm would mean a higher price of capital relative to the (constant) price of labor and, hence, a substitution of labor for capital.

That the correct life must be predicted in order to avoid excessive expenditures may be shown by the following example. Take the case of two firms entering an industry. Each of these firms is constructing a cost curve based on the same type of plant. Engineers of both firms estimate that the real, physical life of the capital equipment will be 33⅓ years. However, the management of Firm A expects that the product will be outmoded in 10 years and that its plant will then become obsolete, while the management of Firm B expects to be able to use the plant for its full physical life. Plant A would depreciate on a 10 per cent per year basis, Plant B on a 3 per cent per year basis. There are two factors of production: Labor and Capital. The price of one unit of labor is $2,000 per year. The initial cost of capital is $100,000 per unit. A particular output can be obtained by any of the following combinations of Labor and Capital:

L	C
. . . units . . .	.
6	1
5	1⅓
4	1¾
3	2⅓
2	3⅓
1	5

The least possible total cost of producing this output is, by definition, the cheapest combination of the two factors. For Firm A this is determined by choosing the minimum expenditure using a price of labor of $2,000 and a price of capital of $100,000 ÷ 10 (assuming no property taxes or opportunity costs) or $10,000.

$$E_A = P_L \cdot L + P_C \cdot C$$
$$= 2{,}000\,L + 10{,}000\,C$$

The least expenditure for A is $22,000 per year, and it uses 6L and 1C.

The prices faced by B, however, are $2,000 for labor and $100,000 ÷ 33⅓, or $3,000 per year. The least expenditure for B is $13,000 per year, and it uses 3L and 2⅓C. These computations are summarized below:

Production Function L	C	Expenditures by A	Expenditures by B
6	1	6 (2000)+1 (10,000)=22,000	6(2000)+1 (3000)=15,000
5	1⅓	5 (2000)+1⅓(10,000)=23,333	5(2000)+1⅓(3000)=14,000
4	1¾	4 (2000)+1¾(10,000)=25,500	4(2000)+1¾(3000)=13,250
3	2⅓	3 (2000)+2⅓(10,000)=29,333	3(2000)+2⅓(3000)=13,000
2	3⅓	2 (2000)+3⅓(10,000)=37,333	2(2000)+3⅓(3000)=14,000
1	5	1 (2000)+5 (10,000)=52,000	1(2000)+5 (3000)=17,000

We have, then, two least possible total costs for the same output simply because there are two expected firm

lives. Furthermore, if A is wrong and B is right about the expected life, then A will spend more to produce the output over a period of 33⅓ years than will B. The total cost to B for 33⅓ years output will be:

$$33\frac{1}{3}\,[3(2000) + 2\frac{1}{3}\,(3000)] = 33\frac{1}{3}\,(6000 + 7000).$$

This is another way of saying that B's total expenditures equal the initial outlay ($233,333) plus the subsequent labor costs (33⅓ [6000]), a total of $433,333. The total cost to A, however, will be $100,000 plus 33⅓ (12,000), since A is using 6L and 1C, while B is using 3L and 2⅓C. A spends $500,000 while B spends only $433,333.

Conversely, if A were right and B were wrong, then B would spend more in ten years then would A. A would spend 10(12,000) for labor, or $120,000, and $100,000 for capital, making a total of $220,000. B would spend only 10(6000) for labor, or $60,000; but it would spend $233,333 for capital, making a total of $293,333. A spends $220,000; B spends $293,333.

Similarly, the price of capital, and therefore the proportions of labor and capital used, will change with variations in interest rates, property tax rates, or annual rent changes. Hence, the optimum combinations of the factors of production for a given process will vary from firm to firm depending on the figures used for these components of the price of capital.

Furthermore, the process of computing the price of capital will change with variations in the method of financing used. Where there is a capital market in which the firm can borrow and lend at will, it is necessary to discount subsequent expenditures to present values (where "present" is the period of construction) in order to determine the optimum combination of the factors of production. Under certain assumptions

concerning financing it would be necessary to use declining balance depreciation or sinking funds. Any of these adjustments would change the price of capital (without affecting the price of labor). Consequently, different optimum combinations would result.

In the present study it is not feasible to compute sets of cost curves for several interest rates, several lengths of life, several methods of financing, etc. Consequently, one set of approximate aggregrate costs was computed as an example. These costs assume a 25-year life of the line amortized in equal annual installments, giving a depreciation rate of 4 per cent per year. An interest rate of 4 per cent per year was assumed, and the annual property tax was estimated to be 1 per cent per year. This gives a total annual price of capital 9 per cent per year.

The optimum combinations of line diameter and horsepower found in this study might differ from those found with other assumptions. However, the pipe line production function is "discrete" in that line pipe (see Section I) is available only in selected sizes. As a result it takes appreciable changes in the price of capital to change the optimum line size for any given throughput. Two test computations, one substituting an interest rate of 10 per cent for 4 per cent, the other using discounted subsequent expenditures, showed that the optimum line size was changed only for small throughputs—and then only by one size. In any event, the basic shapes of the curves are the same regardless of the procedure used.

The aggregated costs are shown in Table 19 and Charts 4 and 5. Table 19 shows total annual costs for each line and throughput studied, together with (average) costs per barrel per 1000 miles. Chart 4 shows annual total costs,

TABLE 19

ANNUAL COSTS OF CRUDE OIL TRUNK PIPE LINE OPERATION—
1000 MILE LINES
(60 SUS, 34° Gravity Oil)

Through-put (Barrels per Day)	Line Diameter	Cost of Horsepower	Cost of Line Diameter	Total Cost of Horsepower and Line Diameter	Other Costs	Total Annual Costs	Costs per Barrel Per 1000 Miles
	(Inches)	.....	Thousands of 1952 Dollars	.....			(Cents)
25,000	8⅝	1,856.4	1,768.0	3,624.4	303.8	3,928.2	43.05
	10¾	708.0	2,164.7	2,872.7*	303.8	3,176.5*	34.81*
	12¾	341.0	2,584.1	2,925.1	303.8	3,228.9	35.39
50,000	8⅝	7,530.5	1,768.0	9,298.5	341.6	9,640.1	52.82
	10¾	3,097.4	2,164.7	5,262.1	341.6	5,603.7	30.70
	12¾	1,451.3	2,584.1	4,035.4	341.6	4,377.0	23.98
	14	967.0	2,823.1	3,790.1*	341.6	4,131.7*	22.64*
	16	542.2	3,324.3	3,866.5	341.6	4,208.1	23.06
	18	328.9	3,925.4	4,254.3	341.6	4,595.9	25.18
75,000	8⅝	23,015.4	1,768.0	24,783.4	379.5	24,162.9	91.92
	10¾	7,913.9	2,164.7	10,078.6	379.5	10,458.1	38.20
	12¾	3,671.5	2,584.1	6,255.6	379.5	6,635.1	24.24
	14	2,406.8	2,823.1	5,229.9	379.5	5,609.4	20.49
	16	1,333.7	3,324.3	4,658.0*	379.5	5,037.5*	18.40*
	18	798.5	3,925.4	4,723.9	379.5	5,103.4	18.64
	20	509.0	4,492.3	5,001.3	379.5	5,380.8	19.66
	22	399.1	4,895.2	5,234.3	379.5	5,613.8	20.51
100,000	10¾	16,028.3	2,164.7	18,193.0	417.3	18,610.3	50.99
	12¾	7,293.0	2,584.1	9,877.1	417.3	10,294.4	28.20
	14	4,795.3	2,823.1	7,618.4	417.3	8,035.7	22.02
	16	2,635.7	3,324.3	5,960.0	417.3	6,377.3	17.47
	18	1,566.7	3,925.4	5,492.1	417.3	5,909.4	16.19
	20	991.0	4,492.3	5,483.3*	417.3	5,900.6*	16.16*
	22	658.9	4,895.2	5,554.1	417.3	5,971.4	16.36
	24	453.2	5,286.7	5,739.9	417.3	6,157.2	16.87
	26	324.4	5,744.7	6,069.1	417.3	6,486.4	17.77
125,000	12¾	12,275.4	2,584.1	14,859.5	455.2	15,044.7	32.97
	14	7,981.1	2,823.1	10,804.2	455.2	11,259.4	24.68
	16	4,360.6	3,324.3	7,684.9	455.2	8,140.1	17.84
	18	2,578.0	3,925.4	6,503.4	455.2	6,958.6	15.25
	20	1,623.7	4,492.3	6,116.0	455.2	6,571.2	14.40
	22	1,072.8	4,895.2	5,968.0*	455.2	6,423.2*	14.08*
	24	735.0	5,286.7	6,021.7	455.2	6,476.9	14.20
	26	523.3	5,744.7	6,268.0	455.2	6,723.2	14.74
	30	286.4	6,524.9	6,811.3	455.2	7,266.5	15.93
150,000	14	12,718.0	2,823.1	15,541.1	493.0	16,034.1	29.29
	16	6,954.1	3,324.3	10,278.4	493.0	10,771.5	19.67
	18	4,078.4	3,925.4	8,003.8	493.0	8,496.8	15.52
	20	2,557.3	4,492.3	7,049.6	493.0	7,542.6	13.78
	22	1,677.4	4,895.2	6,572.6	493.0	7,065.6	12.91
	24	1,148.9	5,286.7	6,435.6*	493.0	6,928.6*	12.66*
	26	812.2	5,744.7	6,556.9	493.0	7,049.9	12.88
	30	439.6	6,524.9	6,964.5	493.0	7,457.5	13.62
	32	339.7	7,048.8	7,388.5	493.0	7,881.5	14.40
200,000	16	13,395.6	3,324.3	16,719.9	568.7	17,288.6	23.68
	18	7,821.6	3,925.4	11,747.0	568.7	12,315.7	16.87
	20	4,886.4	4,492.3	9,378.7	568.7	9,947.4	13.63
	22	3,179.3	4,895.2	8,074.5	568.7	8,643.2	11.84
	24	2,161.6	5,286.7	7,448.3	568.7	8,017.0	10.98
	26	1,526.2	5,744.7	7,270.9*	568.7	7,839.6*	10.74*
	30	820.3	6,524.9	7,345.2	568.7	7,913.9	10.84
	32	621.5	7,048.8	7,670.3	568.7	8,239.0	11.29
250,000	18	13,554.0	3,925.4	17,479.4	644.3	18,123.7	19.86
	20	8,387.2	4,492.3	12,879.5	644.3	13,523.8	14.82

TABLE 19—(*continued*)

Throughput (Barrels per Day)	Line Diameter	Cost of Horsepower	Cost of Line Diameter	Total Cost of Horsepower and Line Diameter	Other Costs	Total Annual Costs	Costs per Barrel Per 1000 Miles
	(Inches)	.....	Thousands of 1952 Dollars	.....			(Cents)
	22	5,438.4	4,895.2	10,333.6	644.3	10,977.9	12.03
	24	3,687.7	5,286.7	8,974.4	644.3	9,618.7	10.54
	26	2,599.9	5,744.7	8,344.6	644.3	8,988.9	9.85
	30	1,375.6	6,524.9	7,900.5*	644.3	9,544.8*	9.36*
	32	1,039.5	7,048.8	8,088.3	644.3	8,732.6	9.57
300,000	20	13,098.4	4,492.3	17,590.7	720.0	18,310.7	16.72
	22	9,467.9	4,895.2	14,363.1	720.0	15,083.1	13.77
	24	5,727.9	5,286.7	11,014.6	720.0	11,734.6	10.72
	26	3,995.4	5,744.7	9,740.1	720.0	10,460.1	9.95
	30	2,124.9	6,524.9	8,649.8	720.0	9,369.8	8.56
	32	1,592.7	7,048.8	8,641.5*	720.0	9,361.5*	8.55*
350,000	22	12,177.3	4,895.2	17,072.5	795.8	17,868.3	13.99
	24	8,217.3	5,286.7	13,504.0	795.8	14,299.8	11.19
	26	5,722.4	5,744.7	11,467.1	795.8	12,262.9	9.60
	30	3,013.9	6,524.9	9,538.8	795.8	10,334.6	8.09
	32	2,267.2	7,048.8	9,316.0*	795.8	10,111.8*	7.92*
400,000	24	11,201.8	5,286.7	16,488.5	871.5	17,360.0	11.89
	26	7,814.7	5,744.7	13,559.4	871.5	14,430.9	9.88
	30	4,012.0	6,524.9	10,626.9	871.5	11,498.4	7.86
	32	3,085.5	7,048.8	10,134.3*	871.5	11,005.8*	7.54*

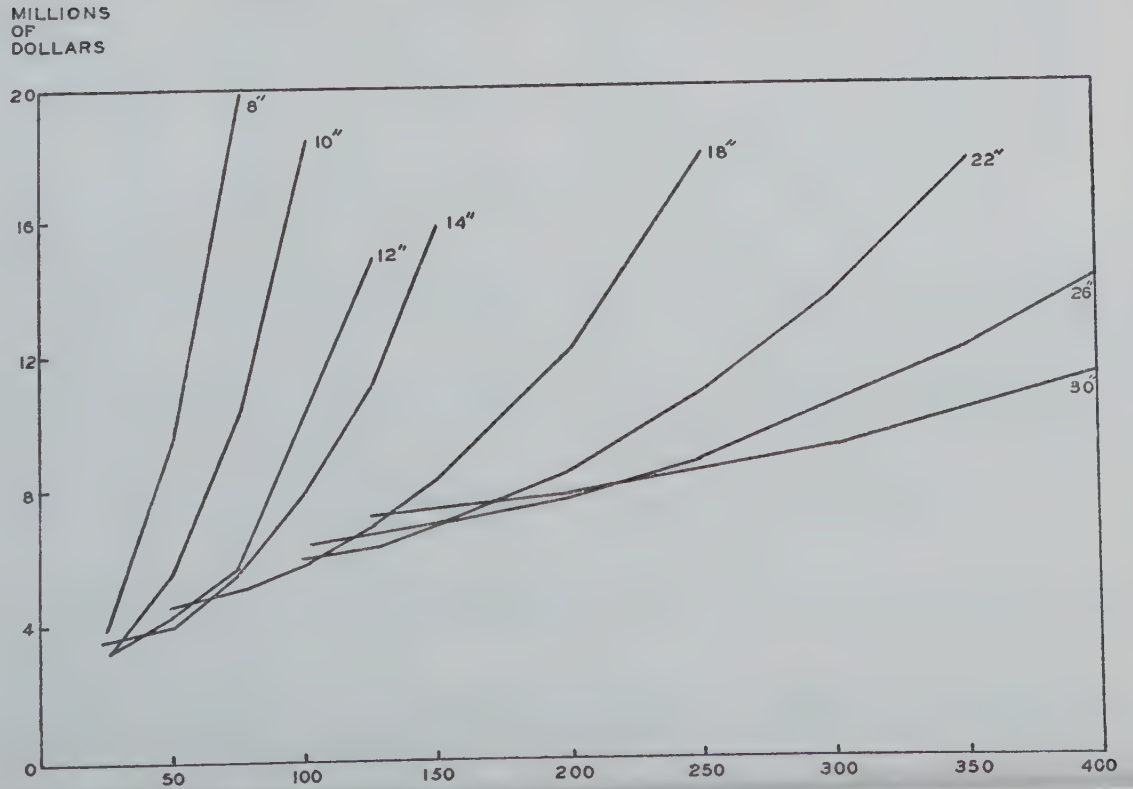
Assumptions: 25 Year Life; 4 per cent interest; 1 per cent per year property tax.
Note: * Optimum line size.

while Chart 5 shows average costs. In these charts, the optimum line for any throughput is that line whose cost curve lies beneath all other cost curves at that throughput. It should be noted that these cost curves are for capacity operation at various designed levels of operation, because the only (short-run) variable cost, electric power, is included at its capacity value. Other (short-run) cost curves would be required for operation of a given line at less than designed capacity.[9]

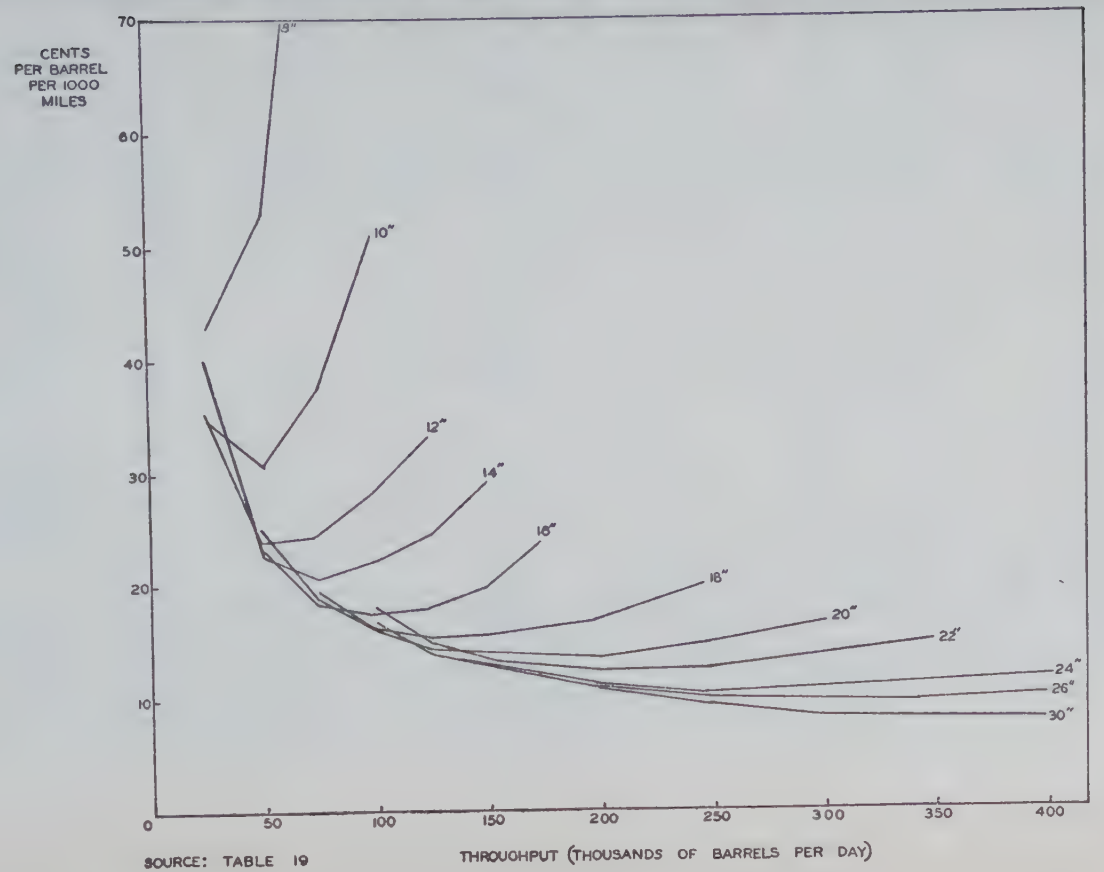
The reader will observe in Chart 5 that costs per barrel per 1000 miles for any given line size are "U" shaped, but that the optimum (least) cost per barrel may be decreased as throughput increases by the use of progressively larger lines. Pipe line operation may, then, be said to exhibit (long-run) decreasing costs, or "economies of scale," throughout the range of standard line sizes available. This means that in

CHART 4

Annual Total Costs of Operating Crude Oil Trunk Pipe Lines.



Costs Per Barrel of Operating Crude Oil Trunk Pipe Lines.



Appendix A

Design Data on Recent Major United States Crude Oil Trunk Line Projects

Company and Location of Line	Approx. Date of Completion	Length (Miles)	Outside Diameter (Inches)	Wall Thickness (Inches)	Capacity (Barrels per Day)	Operating Pressure (p.s.i.)	Approx. Safety Factor (On Bursting Pressure)	Number of Stations	Type of Motive Power	Type of Pumps	Number of Motors & Pumps per Station	Motor Horsepower (H.P.)
Standard (California) Kettelman—Los Midanos, Calif.	1947	176	18	1/4	125,000	900	1.86	2	Electric	Centrif.	3	3–800
Magnolia Corsicana, Tex.—Illinois	1947	647	20	1/2 5/16	100,000	800	3.75	4	Electric	Centrif.	3	3–900
Basin West Texas—Cushing—Okla.	1949	516	24 22 20	9/32 11/32 5/16 1/2	241,000 218,000 183,000	750	2.08 2.27 2.51	4 1	Electric Diesel	Centrif. Centrif.	4 2	3–1250 1–500 2–639
Ozark Cushing, Okla.—Wood River, Ill.	1949	433	22	3/4 11/32	207,000	740	2.54	5	Electric	Centrif.	4	3–1250 1–600
Portland Portland, Me.—Montreal	1949	236	18	1/2 11/32 5/16	127,000	650–700	4.76	6 2	Electric Diesel	Recipr. Recipr.	3 3	3–500 n.a.
Humble West Texas—Houston	1950	370	18	5/16 9/32	135,000	800	2.60	3	Electric	Centrif.	2	2–1000
Atlantic West Texas—S. Tex.	1950	383	10.75	.307	33,000	n.a.	n.a.	1 2	Electric Electric	Centrif. Centrif.	2 2	2-600 2–350
Mid-Valley E. Texas—Lima, Ohio	1950	933	22 20	11/32 5/16 9/32	107–157,000	750 935 1030	2.01 2.75 2.00	3 2 2	Electric Diesel Dual-Fuel	Centrif. Centrif. Centrif.	2 2 2	2–1500 2–1750 2–800

APPENDIX A—*Continued*

Company and Location and Line	Approx. Date of Completion	Length (Miles)	Outside Diameter (Inches)	Wall Thickness (Inches)	Capacity (Barrels per Day)	Operating Pressure (p.s.i.)	Approx. Safety Factor (On Bursting Pressure)	Number of Stations	Type of Motive Power	Type of Pumps	Number of Motors & Pumps per Station	Motor Horsepower (H.P.)
Interprovincial Alberta— Superior, Wis.	1950	450	20	5/16 9/32	145,000 60,000	1050	1.79	4	Diesel	Centrif.	4	4-1080
Sinclair Drumright, Okla.— East Chicago	1952	675	24 22	11/32 9/32	280,000 150,000	680	2.53 2.76	4 4	Electric Electric	Centrif. Centrif.	4 4	3-1750 1-900 3-1250 1-600
Platte Wyoming—Wood River, Illinois	1952	1080	20	5/16 11/32	90,000	1000	2.06	4	Electric	Centrif.	4	3-800 1-350
West Texas—Gulf[1] W. Texas—E. Texas— Gulf Coast	1953	469	26 20	11/32 1/4	380,000	900	1.76 2.29	5 1 1	Electric Electric Electric Electric	Centrif. Centrif. Centrif. Centrif.	4 4 6	3-2000 1-1000 3-1000 1-500 3-1500 1-800 1-2000 1-1000
Rancho[1] W. Texas—Houston	1953	463	24	11/32 5/16	345,000	800	2.15	8	Electric	Centrif.	3	3-1750 1-900

Notes: [1] Ultimate capacity. n.a.—Not available.
Source: Compiled from information in trade journal articles (*World Oil*, *Pipe Line News*, *Oil and Gas Journal*, and *Petroleum Engineer*) and private sources.

order to realize the least possible transportation costs, oil must be carried conglomerately in as large quantities as is possible. The optimum (outside-diameter) line size for large throughputs will be about 30 inches in most cases, and would probably never be less than 26 inches (the largest pipe yet used for crude in the United States)—unless very short lives and/or high interest rates were assumed. It may be concluded that for efficient transportation, pipe lines must be big and that future lines to any large new fields should, in all likelihood, be larger than those now in operation in the United States.

LESLIE COOKENBOO, JR.

NOTES

1. R. L. Huntington and others, *High Pressure Pipe Line Research* (Olean, N.Y., 1947).
2. G. C. Hughes, *The Preliminary Design of Crude Oil Trunk Systems* (Austin, 1949), unpublished Master's thesis deposited in the Library of the University of Texas.
3. Assume that the intercept of one line equals $\frac{E_1}{P_L}$ and that the intercept of the other equals $\frac{E_2}{P_L}$. Since $P_L = P_L$, the line of this pair which has the higher intercept will have the higher E. If $E_2 > E_1$, then its line will have the higher intercept.
4. See Petroleum Administration for Defense, *Transportation of Oil* (Washington, 1951), p. 25.
5. G. C. Hughes, *Preliminary Design*, p. 3.
6. See U. S. Interstate Commerce Commission, *Statistics of Oil Pipe Lines, 1951* (Washington, 1952).
7. See J. H. Sybert, *Economic Selection of a Crude Oil Pipe Line* (Austin, 1948), unpublished Master's thesis deposited in the Library of the University of Texas, p. 83.
8. J. H. Sybert, *Economic Selection*, Appendix I.
9. See the discussion of short-run costs in L. Cookenboo, Jr., *Crude Oil Pipe Lines and Competition in the Oil Industry* (forthcoming, 1954), Chapter I.

BIBLIOGRAPHY

The following is a list of some of the pipe line costing studies done in the past two decades. Of these, the most important is Mr. Hughes' thesis.

Chenerey, H. B., *Engineering Bases of Economic Analysis* (Cambridge, Massachusetts, 1950), unpublished Doctoral thesis, deposited in Widener Library of Harvard University.

Hill, E. G., "Engineering Economics of Long Petroleum Pipe Lines," American Institute of Mining and Metallurgical Engineers, *Transactions*, Petroleum Division, *Petroleum Development and Technology* (1942), p. 231.

Hughes, G. C., *The Preliminary Design of Crude Oil Trunk Systems* (Austin, 1949), unpublished Master's thesis deposited in the Library of the University of Texas.

Huntington, R. L., and others, *High Pressure Pipe Line Research* (Olean, N.Y., 1947).

Kennedy, W. C., Jr., and G. G. Stueve, "Sizing Crude Oil Pipe Lines," *Oil and Gas Journal*, September 21, 1953, p. 183. (Based on the Hughes thesis.)

Sybert, J. H., *The Economic Selection of a Crude Oil Pipe Line* (Austin, 1948), unpublished Master's thesis deposited in the library of the University of Texas.

Young, F. R., "Applied Design and Economics of Pipe Lines," *Oil and Gas Journal*, November 8, 1934, p. 38.